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NASA-CR-171230) SPACE POWER DISTRIBUTION
SYSTEM TECHNOLOGY. VOLUME 3: TEST FACILITY
DESIGN Final Report (TRW Defense and Space
Systems Group) 89 p HC A05/MF A01 CSCI 22B

N85-12936

Unclass

G3/20 24547

Final Report

Space Power Distribution System Technology

Volume 3 Test Facility Design

TRW Report Number 34579-6001-UT-00

March 1983

Contract NAS8-33198



Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812



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FOREWORD

This report documents in three volumes the work performed by TRW Electronics and Defense Sector, Redondo Beach, California, for George C. Marshall Space Flight Center (NASA/MSFC), Huntsville, Alabama, under contract NAS8-33198 (TRW Sales Number 34579).

Volume 1, "Reference EPS Design," summarizes the work under Task 1, System Design and Technology Development; Volume 2, Autonomous Power Management, summarizes the work under Task 2, Power Management Subsystem Development; and Volume 3, Test Facility Design, summarizes the work under Task 3, AMPS Test Facility. This final report is submitted in compliance with the contract statement of work and covers the entire period of performance from 05 December 1978 through 31 March 1982.

These three tasks were structured to define, develop, and demonstrate technology for autonomous management of complex multi-hundred-kilowatt electrical power subsystems for orbital spacecraft. Initially, a conceptual design of a reference electrical power subsystem was developed from spacecraft level life cycle cost analyses of 1985-86 technology for solar array, energy storage, and power distribution, including shuttle transportation and orbital drag makeup propulsion (Volume 1). This reference electrical power subsystem was subsequently utilized to quantify the benefits of the power management approach and to demonstrate the power management subsystem concept (Volume 2). It is important to recognize that the resultant power management technology (strategies and hardware) has application to a broad spectrum of electrical power systems and is independent of power level, distribution voltage and form (ac or dc), payload type, spacecraft mission, and orbital parameters.

This study was managed for TRW by Charles Sollo of the Electrical Power Systems Laboratory, and for NASA/MSFC by Jim Graves of the Power Branch. The principal contributors for this technical study task and preparation of this report volume include D. Kent Decker, Marshall D. Cannady, John E. Cassinelli, Bertrand F. Farber, Charles Lurie, Gerald W. Fleck, Jack W. Lepisto, Alan Messner, and Paul F. Ritterman. Their participation is gratefully acknowledged.

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1. INTRODUCTION

The consideration of a 250-kilowatt electrical power system is a major step in the economical generation of electrical power in space. This power level represents two orders of magnitude increase in power capability over that presently utilized on typical satellites and a greater power capability than the Shuttle. The reference approach to this power system (Volume 1) incorporates autonomous management of a large number of modest power rating components to attain the aggregate electrical power system capacity (250 kW). Autonomy, high-voltage high-power devices, and the scale of integration are new. Hence, a working breadboard of the reference electrical power system approach is needed to develop and test the management strategies, the control algorithms, new equipment, and system interactions, and to compare actual system behavior and performance with the predictions from computer models of large-scale electrical power systems. The AMPS Test Facility is therefore conceptually designed as an evolving tool to fulfill these goals.

The AMPS Test Facility conceptual design integrates the power hardware (Volume 1) and the power management hardware (Volume 2) into three representative power channels of the 17 channels of the reference electrical power system design (Volume 1). Each power channel of the AMPS Test Facility is rated at 16 kilowatts, for a total Test Facility capacity of 48 kilowatts. The Test Facility consequently includes 48 kilowatts of load divided between two load centers. The Test Facility requires various hardware simulations or substitutions whenever spacecraft designed equipment is not available or appropriate.

2. EXECUTIVE SUMMARY

The consideration of a 250-kilowatt electrical power system is a major step in the economical generation of electrical power in space. The reference approach to this power system incorporates the autonomous management of a large number of modest power rating components to attain the aggregate electrical power system capacity (250 kilowatts). Autonomy, high-voltage high-power devices, and the scale of integration are new. Hence, a breadboard of the reference electrical power system approach is needed to develop and test the management strategies, the control algorithms, new equipment, and system interactions, and to compare actual system behavior and performance with the predictions from computer models of large-scale electrical power systems. The AMPS Test Facility is conceptually designed as an evolving tool to fulfill these needs.

The AMPS Test Facility conceptual design incorporates three power channels representative of the 17 channels of the reference electrical power system design. Each power channel of the AMPS Test Facility is rated at 16 kilowatts, for a total Test Facility capacity of 48 kilowatts. The Test Facility consequently includes 48 kilowatts of load divided between two load centers. The Test Facility requires various hardware simulations or substitutions whenever spacecraft designed equipment is not available or appropriate.

2.1 SCOPE

The primary goal of the reference electrical power system and autonomous power management is to attain more economical space power. The AMPS Test Facility is a major tool on the development path to this goal. The ultimate goals of the Test Facility are to:

- 1) Demonstrate the feasibility of the reference electrical power system concept.
- 2) Provide a test bed to develop and evaluate the strategies for the management and control of a spacecraft electrical power system.
- 3) Demonstrate the feasibility and performance benefits of autonomous power management.

- 4) Provide a system-level test bed to integrate spacecraft component designs (breadboards, engineering models, etc.) and thereby evaluate interface interactions early with full-scale hardware and system-level operation.
- 5) Provide a data base of operational performance with high-power equipment for comparison to, and evaluation of, performance predictions from computer models of electrical power systems.
- 6) Develop requirements for new technology.

The AMPS Test Facility concept is designed to economically fulfill these goals.

2.2 REQUIREMENT DEFINITION

Guidelines for the Test Facility, denoted in the statement of work for Task 3, direct the conceptual definition of a high-voltage, high-power Test Facility representative of at least three channels of the reference electrical power system. Power generation, energy storage, and fault protection equipment, loads, and power management subsystem hardware are to be included in the Test Facility. In addition, simulation of failure modes is to be included. Also, components of the Test Facility are to be replaceable by advanced technology hardware as it becomes available.

The major requirements for the Test Facility (Table 2-1) are formulated from these guidelines and the implications inherent in them. In addition, an operational readiness date compatible with support of the NASA space station program is considered essential.

Certain constraints are also implicit in the definition of a high-power Test Facility. Such constraints are derived primarily from considerations of:

- 1) Practicality
- 2) Availability
- 3) Economy.

These considerations generally limit the employment of spacecraft designed hardware and dictate the substitution of equipment with similar performance characteristics or in certain cases the design and development of specialized equipment to simulate specific hardware performance characteristics.

Table 2-1. Requirements

1. Simulate a representative portion (at least three channels) of the 250-kilowatt reference electrical power system including power sources, energy storage, and power control.
2. Simulate representative loads.
3. Simulate orbital operational sequences.
4. Simulate faults, out-of-tolerance conditions, and failures.
5. Provide status data gathering, recording, and display.
6. Incorporate the power management subsystem.
7. Simulate control commands originating beyond the power management subsystem.
8. Demonstrate autonomous power management.
9. Accommodate replacement of simulation equipment with spacecraft components, equipment, and units (breadboards, engineering models, preproduction units, or qualification units).
10. Accommodate expansion of channel power capacity and of Test Facility aggregate load power.
11. Support technology development for application on the initial space station or space platform program.

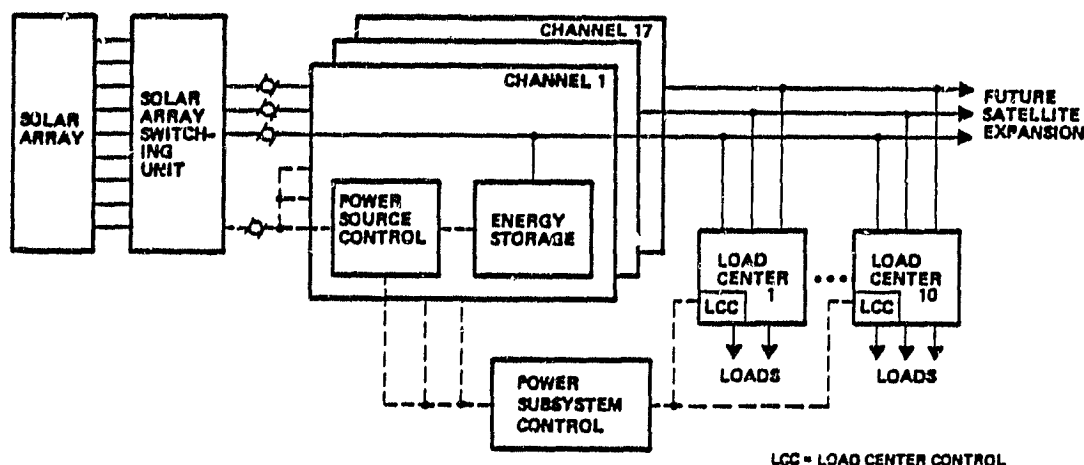
2.3 TEST FACILITY CONCEPT

The design of a Test Facility entailed identification of the relevant components of the reference electrical power system for inclusion in the Test Facility, adaptation of the exterior interfaces of the electrical power system and its power management subsystem for control stimuli and status monitoring, and selection of suitable substitutions or simulations for major components. In addition, complementary controls and displays were defined and suitable anomalies and operational procedures were identified for utilization with the Test Facility.

2.3.1 Reference Electrical Power System

The reference electrical power system (Volume 1) is configured as seventeen 16-kilowatt channels (Figure 2-1) to support 250 kilowatts of payload power demand and 22 kilowatts of housekeeping equipment - predominantly liquid coolant pumps in the thermal subsystem. Each channel includes one 160-cell, 150-ampere-hour, nickel-hydrogen battery for energy storage in support of a 36-minute eclipse at full power (272 kilowatts). Each channel consists of one primary power bus that is electrically isolated from the other channels (no tie connections), but all channels utilize a common power return path. These isolated power channels are integrated into a cohesive operating utility by the Power Management Subsystem (Volume 2).

Power is generated by a solar array and is controlled and allocated to the respective power channels by a solar array segment switching unit in accordance with the needs of the loads and batteries. This switching unit connects sufficient solar array segments to each power channel primary bus to provide the load power demand and the battery charging current of that channel. The power management subsystem monitors the loads, batteries, and



GENERATION - CASSEGRAIN CONCENTRATOR SOLAR ARRAY
 ENERGY STORAGE - NICKEL-HYDROGEN BATTERY (160, 150-AH CELLS)
 BATTERY CHARGER - SOLAR ARRAY SWITCHING UNIT
 REGULATION - 220 ± 20 VOLTS (BATTERY CHARACTERISTICS)
 POWER TRANSMISSION - DIRECT CURRENT AT SOURCE VOLTAGE
 POWER DISTRIBUTION - DIRECT CURRENT AT SOURCE VOLTAGE
 POWER PROCESSING - AS NEEDED WITHIN EACH PAYLOAD OR LOAD CENTER
 CHANNEL QUANTITY - DEFINED BY ENERGY STORAGE
 RELIABILITY - FAIL OPERATIONAL, FAIL SAFE
 GRACEFUL CAPACITY DEGRADATION WITH FAILURES
 LIFE - INDEFINITE; REPLACE FAILED UNIT AT NEXT SERVICE OPPORTUNITY

Figure 2-1. Multichannel Reference Electrical Power System Design

solar array, and selects the appropriate solar array segment switch closures to produce the desired solar array output current to each channel, i.e., payload current plus desired battery charging current. Power transmission and distribution are at the power source voltage which is regulated by the voltage characteristics of the directly connected battery.

Multikilowatt space platform payloads are typically the aggregate of many smaller individual loads in the range of 100 to 200 watts each. Hence, power source buses of multi-hundred-kilowatt capacity are not required to support individual loads. Further, by providing alternate connection options for each load to several main distribution buses, direct paralleling of the power source channels is not required to achieve redundancy (Figure 2-2). Parallel operation of batteries is avoided, yet redundancy is enhanced without adding power source capacity and incurring its cost.

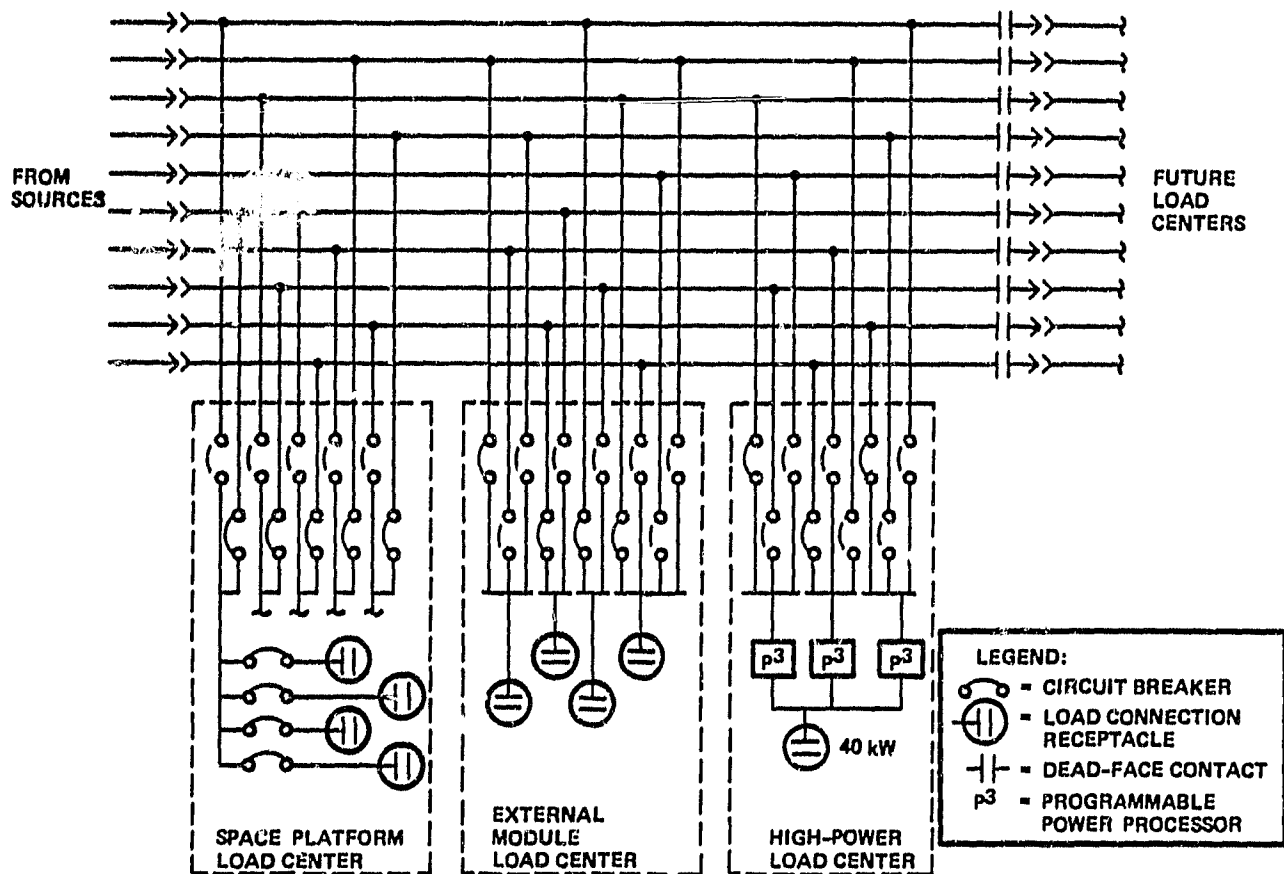


Figure 2-2. Power Distribution Concept

2.3.2 Conceptual Design

The conceptual design for the AMPS Test Facility, Figure 2-3, comprises the three power channels, each representative of one of the 17 channels of the reference electrical power system (Figure 2-1). Each channel of the Test Facility is rated at 16 kilowatts, for a total Test Facility capacity of 48 kilowatts. The Test Facility includes two identical load centers of 24 kilowatts each. The Test Facility incorporates various hardware simulations or substitutions when spacecraft equipment prototypes are not immediately available or necessarily appropriate. Major equipment items of the Test Facility are summarized in Table 2-2.

The Test Facility concept (Figure 2-3) also includes a Control Center to provide the interface simulation between the electrical power system and the spacecraft computer, ground controller, and test center personnel (or equivalent onboard spacecraft personnel). Video displays and a computer keyboard (terminal) are provided to enable personnel to communicate with the power management subsystem of the electrical power system and with the simulation profile controller. In addition, display panels, similar to utility generation station status panels, are included to display the continuing status of the electrical power system.

The Test Facility is arranged into two major rooms (Figure 2-4): a distribution room, and an energy storage room. The energy storage room is isolated due to ventilation requirements for safe control of any hydrogen gas evolved from the batteries. The energy storage room contains the battery cells, the power source controller and associated battery monitor electronics, and the battery ancillary panels. The solar array simulators, load centers, and control equipment are located in the distribution room. Resistive elements of the loads are located just exterior to the distribution room to minimize the cooling and air circulation requirements imposed upon the climate/environmental control system of the building.

2.3.3 Anomaly Simulation

A repertoire of generic anomalies (Table 2-3) for the electrical power system is included in the Test Facility conceptual design. These anomalies provide the stimuli to exercise the power management control strategies,

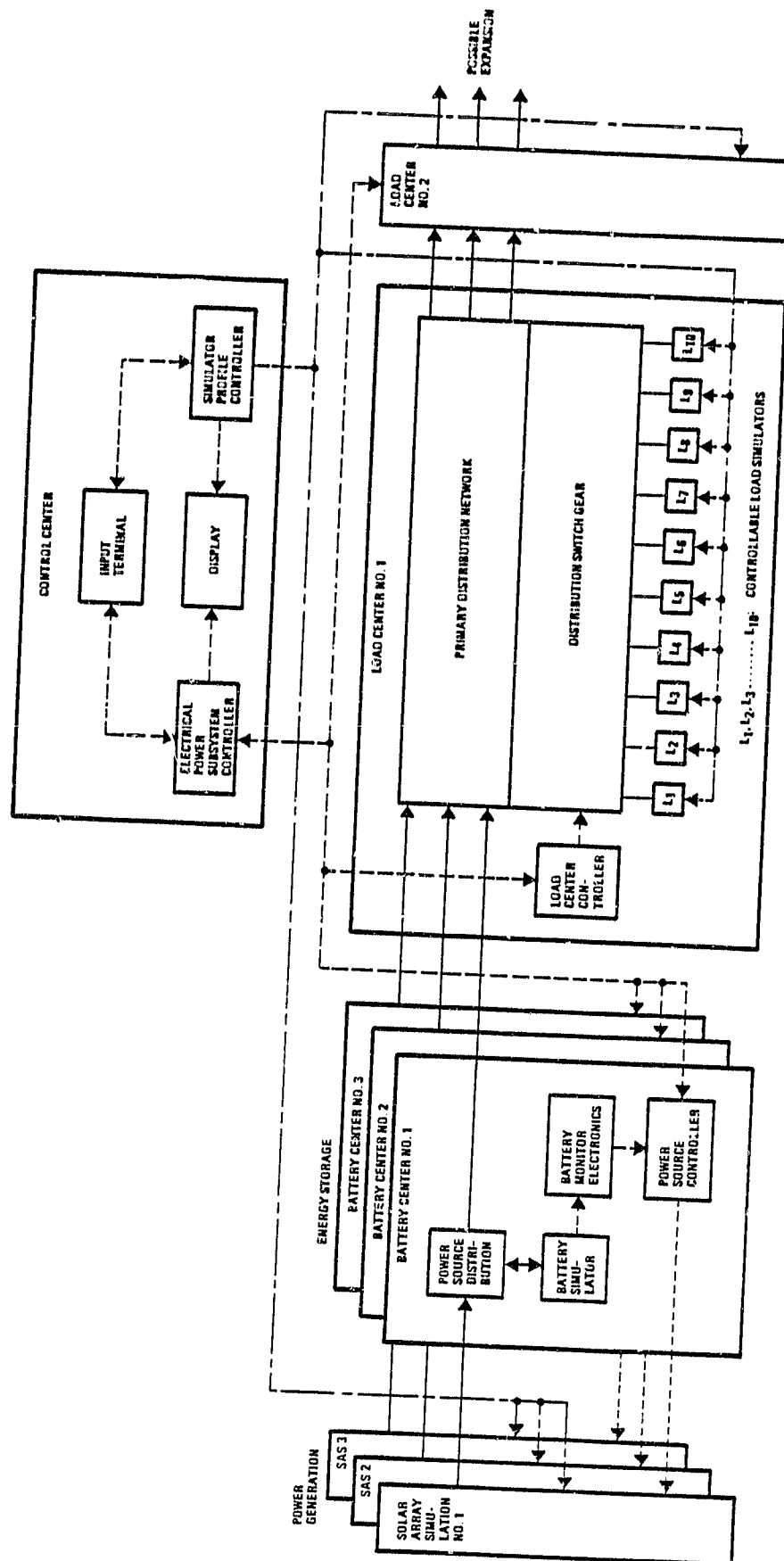


Figure 2-3. Test Facility Concept

Table 2-2. Test Facility Major Item Equipment List

Location	Item	Quantity
Power Generation		1
	Solar Array Simulator	3
Energy Storage		1
	Battery Substitute	3
	Power Source Controller (Includes Battery Monitor Electronics)	3
	Battery Ancillary Panel	3
	Power Supply (Trickle Charger)	3
Load Center		2
	Resistive Loads	9
	Pulse Load Simulator	1
	Switch Gear (Substitutes)	10
	Load Center Controller	1
Control Center		1
	EPS Controller	1
	Simulation Profile Controller	1
	Video/Keyboard Terminals	2
	Printer	1
	Primary Control Panel	1
	Wall Status Display	1
	Data Recording Equipment	1 set
Subflooring		
	Distribution Wiring	
	Channel Power Transmission Lines	24
	Data Bus Lines	10
	Simulation Control Lines	200
	120 V, 60 Hz Ancillary Power Lines	30
	440 V, 3 phase, 60 Hz, Y-connected, 100 KVA Lines	12

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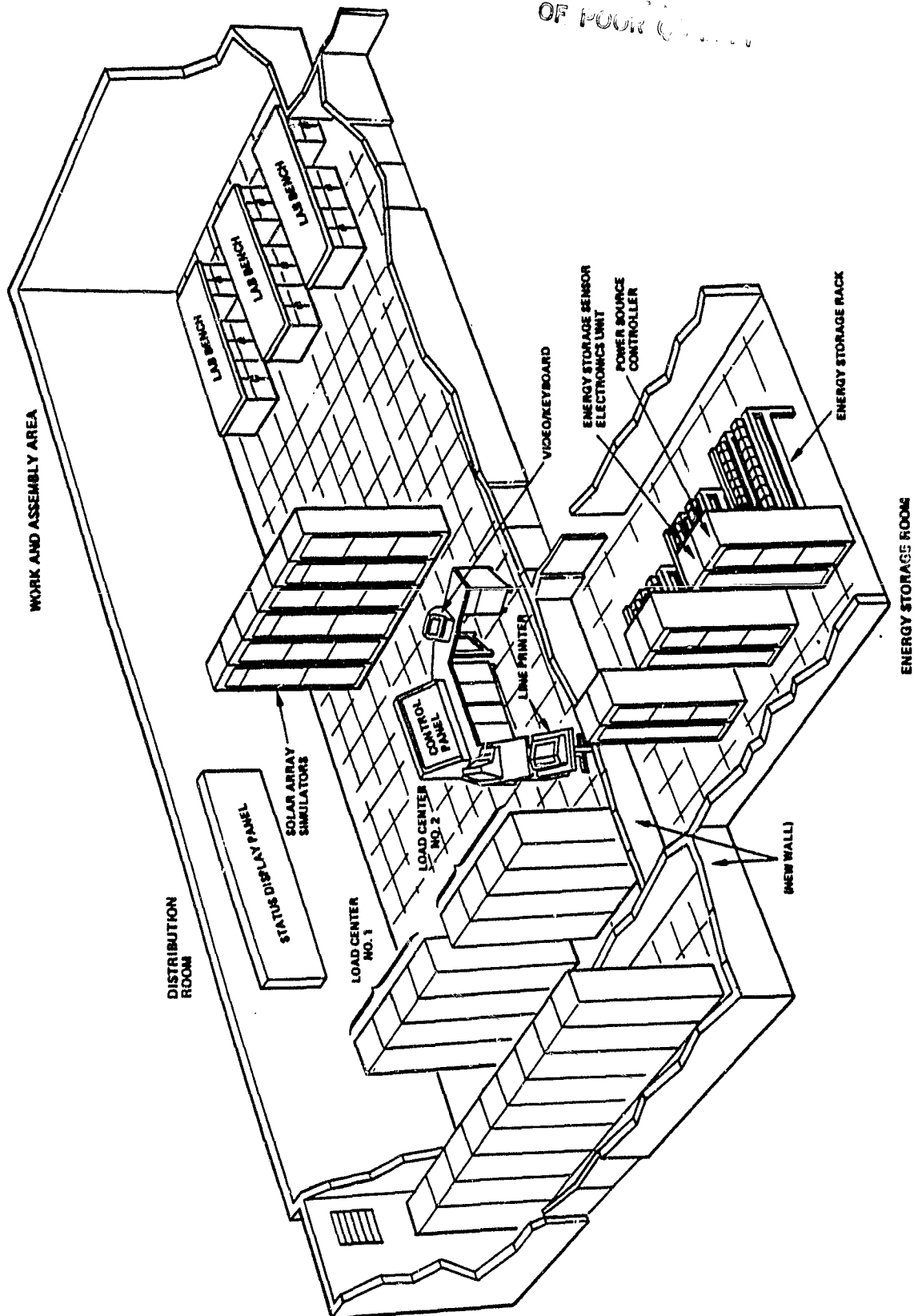


Figure 2-4. Test Facility Physical Layout

Table 2-3. Generic EPS Anomalies

Equipment	Failure Mode Simulated	Implementation
Battery	Poor Cell Performance (Low Voltage, Slow Charging)	High Resistance Shunt of Cell
	Shorted Cell*	Low Resistance Shunt of Cell
	Open Cell	Main Circuit Breaker Opened
	Inoperative Cell Monitor	Open Cell Monitor Wire
Switchgear	Faulted Opened or Closed	Interrupt Command Line
	Invalid Status Data	Open Switchgear Monitor Wire Monitor Signal Grounded Monitor Signal Connected to Signal Power
Solar Array	Degraded Output	Limit Simulator Output Voltage and Current
Primary Bus	Ground Fault*	Apply Short
	Overload	Apply Added Load (10 kW)

* Caution must be exercised in simulating shorted or ground faulted conditions as very high power surges can be attained with the battery capacity supporting each channel.

the equipment control laws (algorithms), and autonomous operation to accommodate and/or tolerate (isolate) anomalies. Evaluation of the software for this critical function is thereby implemented.

The anomalies involve the major failure modes that could occur during electrical power system operation: switchgear, load, and battery problems. Additional anomalies, associated with the status monitoring and data gathering from the electrical power system that are required for automated control and management decisions, are also included. These anomalies provide the stimuli for ultimately demonstrating validation techniques incorporated in interface hardware and in data acquisition software. The repertoire of anomalies may be expanded in the future as the development of the automation technology matures sufficiently to address redundancy requirements and their implementation in software coding, computational and decision processing, and data transfer (data buses).

2.4 TRADE ANALYSES

The Test Facility requires various hardware simulations or substitutions whenever spacecraft or prototype equipment is not available or necessarily appropriate. Two major analyses were undertaken in identifying the most effective approach for Test Facility equipment:

- 1) Selection of the energy storage simulation approach
- 2) Evaluation of dissipation versus regeneration of load power.

A substitution of commercial nickel-cadmium cells for the nickel-hydrogen cells of the energy storage approach in the reference electrical power system was determined to provide excellent performance simulation, to be cost effective, and hence to be the practical approach. Resistive loads were selected because regeneration was not cost effective. These results are incorporated in the definition of the Test Facility.

2.4.1 Energy Storage Simulation

The energy storage for each channel of the reference electrical power system is a 160-cell, 150-ampere-hour nickel-hydrogen battery. Similar energy storage performance is therefore required for each channel of the Test Facility. However, these 150-ampere-hour nickel-hydrogen cells are not presently available, and development is required to achieve technology readiness by 1986. Consequently, neither spacecraft nor prototype 150-ampere-hour nickel-hydrogen cells are available for application in the Test Facility. Six approaches were identified to provide the requisite energy storage performance. Each approach was analyzed for its replication of pertinent nickel-hydrogen performance characteristics, for its procurement cost, and for its availability (development status). Commercial nickel-cadmium cells were selected to essentially replace the 150-ampere-hour nickel-hydrogen cells of the reference electrical power system on a one-for-one basis. These commercial nickel-cadmium cells closely simulate the electrical performance of nickel-hydrogen cells during discharge and recharge. Overcharge and thermal conditions, of little relevance to the operation of the Test Facility, are not simulated.

2.4.2 Dissipation Versus Regenerative Loads

The two load centers aggregate 48 kilowatts of power. An option exists to pump the power of these loads back into the facility alternating current (60 hertz) utility source (regeneration) rather than dissipate this power as heat with resistive load elements. This regenerative approach has attractive conservation and environmental connotations. However, the economics of the regeneration option are poor, requiring over 6 years of continuous full power use (24 hours/day, 365 days/year) to break even. Normal use, 40 hours/week, 50 weeks/year, results in over 26 years to break even - a poor investment. Hence, the resistive load bank approach is recommended and incorporated in the Test Facility conceptual design.

3. SCOPE

The primary goal of this study of the reference electrical power system and autonomous power management is to attain more economical space power. The AMPS Test Facility is a major tool on the development path to this goal. The interim goals of the Test Facility are to:

- 1) Demonstrate the feasibility of the reference electrical power system concept.
- 2) Provide a test bed to develop and evaluate the strategies for the management and control of a multichannel electrical power system.
- 3) Demonstrate the feasibility and performance benefits of autonomous power management.
- 4) Provide a system-level test bed to integrate spacecraft component designs (breadboards, engineering models, etc.) and thereby evaluate interface interactions early with full-scale hardware and system-level operation.
- 5) Provide a data base of operational performance with high-power equipment for comparison to and evaluation of performance predictions from computer models of electrical power systems.
- 6) Develop requirements for new technology.

The AMPS Test Facility concept is designed to economically fulfill these goals.

4. REQUIREMENTS DEFINITION

Guidelines for the AMPS Test Facility are denoted in the statement of work for Task 3 (Appendix A of Volume 1). These guidelines, summarized in Table 4-1, direct the conceptual definition of a high-voltage, high-power Test Facility representative of at least three channels of the reference electrical power system (Volume 1). Power generation, energy storage, fault protection equipment, loads, and power management subsystem hardware are to be included in the Test Facility. In addition, simulation of failure modes is to be included. Also, components of the Test Facility are to be replaceable by advanced technology hardware as it becomes available.

The major requirements for the AMPS Test Facility (Table 4-2) are formulated from these guidelines and the implications inherent in them. In addition, an operational readiness date compatible with support of the NASA space station program is considered essential.

Constraints are also implicit in the definition of a high-power Test Facility. Such constraints are derived primarily from considerations of:

- 1) Practicality
- 2) Availability
- 3) Economy.

These considerations limit the employment of spacecraft designed hardware and dictate the substitution of equipment with similar performance characteristics or in certain cases the design and development of specialized equipment to simulate specific hardware performance characteristics. For example, it is impractical to utilize a multikilowatt solar array for the power source of the Test Facility. The solar array is excessively large, awkward to handle, difficult to illuminate evenly (and to eclipse fully), and expensive. Simulation with a specifically designed power supply is a practical solution.

Funding is always limited. Hence, major power components need to be represented by substituting their commercial counterparts or simulated rather than utilizing expensive spacecraft designed and packaged equipment.

Table 4-1. Study Guidelines

1. Represent three channels of the 250 kilowatt reference power system.
2. Utilize high-voltage, high-power components.
3. Include power generation, energy storage, protection hardware, and loads.
4. Incorporate power management subsystem hardware.
5. Simulate failure modes and abnormal conditions.
6. Record system operational performance.
7. Allow equipment replacement and upgrading.

Table 4-2. Requirements

1. Simulate a representative portion (at least three channels) of the 250 kilowatt reference electrical power system including power sources, energy storage, and power control.
2. Simulate representative loads.
3. Simulate orbital operational sequences.
4. Simulate faults, out-of-tolerance conditions, and failures.
5. Provide status data gathering, recording, and display.
6. Incorporate the power management subsystem.
7. Simulate control commands originating outside the power management subsystem.
8. Demonstrate autonomous power management.
9. Accommodate replacement of simulation equipment with spacecraft components, equipment, and units (breadboards, engineering models, preproduction units, or qualification units).
10. Accommodate expansion of channel power capacity and of Test Facility aggregate load power.
11. Support technology development for application on the initial space station or space platform program.

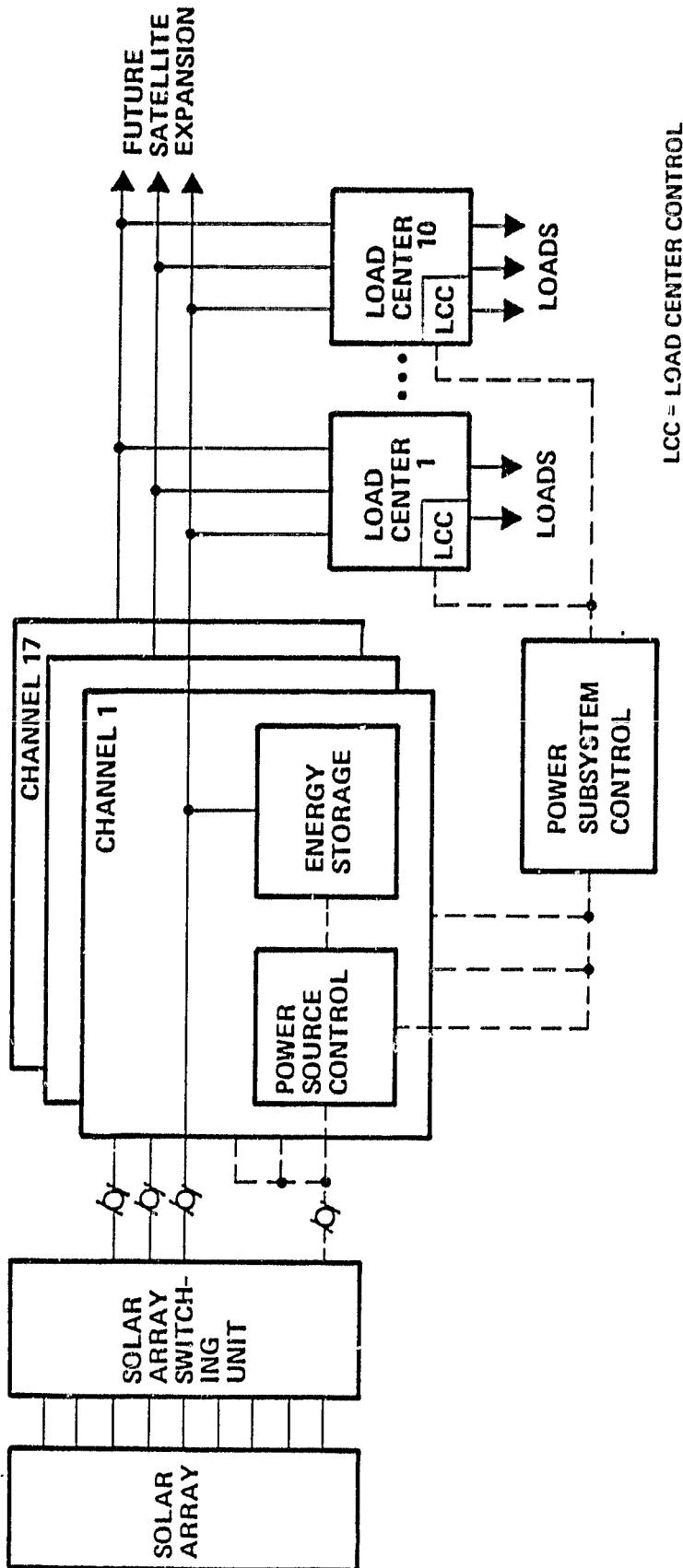
5. TEST FACILITY CONCEPT

The design of a Test Facility entails identification of the relevant components of the reference electrical power system for inclusion in the Test Facility, adaptation of the exterior interfaces of the electrical power system and its power management subsystem for control stimuli and status monitoring, and selection of suitable substitutions or simulations for major components. In addition, complementary controls and displays must be defined, and suitable anomalies and operational procedures identified, for utilization with the Test Facility.

5.1 REFERENCE ELECTRICAL POWER SYSTEM

The reference electrical power subsystem (EPS) is configured as seventeen 16-kilowatt channels (Figure 5-1) to support 250 kilowatts of payload power demand and 22 kilowatts of housekeeping equipment. Each channel includes one 160-cell, 150-ampere-hour, nickel-hydrogen battery for energy storage in support of a 36-minute eclipse at full power (272 kilowatts). Each channel consists of one primary power bus that is electrically isolated from the other channels (no tie connections), but all channels utilize a common power return path. These isolated power channels are integrated into a cohesive operating utility by the Power Management Subsystem (Volume 2).

Power is generated by a Cassegrain concentrator solar array composed of miniature elements. The generated power is controlled and allocated to the respective power channels by a solar array switching unit (SASU) in accordance with the needs of the payloads and batteries. This switching unit connects sufficient solar array segments to each power channel primary bus to provide the load power demand and the battery charging current of that channel. The power management subsystem (PMS) monitors the loads, batteries, and solar array, and selects the appropriate switch closures to produce the desired solar array output current to each channel - payload current plus desired battery charging current. The bus voltage therefore fluctuates from the low extreme of 200 volts at end of battery discharge to the upper extreme of 240 volts at end of recharge. Power transmission and



GENERATION – CASSEGRAIN CONCENTRATOR SOLAR ARRAY
 ENERGY STORAGE – NICKEL-HYDROGEN BATTERY (160, 150-AH CELLS)
 BATTERY CHARGER – SOLAR ARRAY SWITCHING UNIT
 REGULATION – 220 ± 20 VOLTS (BATTERY CHARACTERISTICS)
 POWER TRANSMISSION – DIRECT CURRENT AT SOURCE VOLTAGE
 POWER DISTRIBUTION – DIRECT CURRENT AT SOURCE VOLTAGE
 POWER PROCESSING – AS NEEDED WITHIN EACH PAYLOAD OR LOAD CENTER
 CHANNEL QUANTITY – DEFINED BY ENERGY STORAGE
 RELIABILITY – FAIL OPERATIONAL, FAIL SAFE
 GRACEFUL CAPACITY DEGRADATION WITH FAILURES
 LIFE – INDEFINITE; REPLACE FAILED UNIT AT NEXT SERVICE OPPORTUNITY

Figure 5-1. Multichannel Reference Electrical Power System Design

distribution are at the power source voltage which is regulated by the voltage characteristics of the directly connected battery.

Multikilowatt space platform payloads are typically composed of several smaller individual loads in the range of 100 to 200 watts each. Hence, power source buses of multi-hundred-kilowatt capacity are not required to support individual loads. The reference distribution approach incorporates 17 power source channels, each supported by a single, nickel-hydrogen battery and each power source channel forms a main distribution bus (Figure 5-1). Further, by providing alternate connection options for each load to several main distribution buses, direct paralleling of the power source channels is not required (Figure 5-2). Parallel operation of batteries (without isolation by secondary power converters) is avoided, and redundancy is enhanced without adding power source capacity and the associated cost. For very high power loads, power may be drawn from several power channels by paralleling the outputs of several programmable power processors (Figure 5-2). Reverse power flow is thereby precluded, and programmable power usage from the multiple source channels is attainable. Transformer isolation can be added to these processors if desired.

5.2 CONCEPTUAL DESIGN

The conceptual design for the AMPS Test Facility, Figure 5-3, comprises three power channels, each representative of one of the 17 channels of the reference electrical power system (Figure 5-1). Each channel of the Test Facility is rated at 16 kilowatts, for a total Test Facility capacity of 48 kilowatts. The Test Facility includes two identical load centers of 24 kilowatts each. The Test Facility incorporates various hardware simulations or substitutions whenever spacecraft equipment or prototypes are not available or not appropriate. Major equipment items of the Test Facility are summarized in Table 5-1.

The Test Facility concept (Figure 5-3) also includes a control center to provide the interface simulation between the electrical power system and the spacecraft computer, ground controller, and test center personnel (or equivalent onboard spacecraft personnel). Video displays and computer keyboards (terminals) are provided to enable personnel to communicate with the power management subsystem of the electrical power system and with the

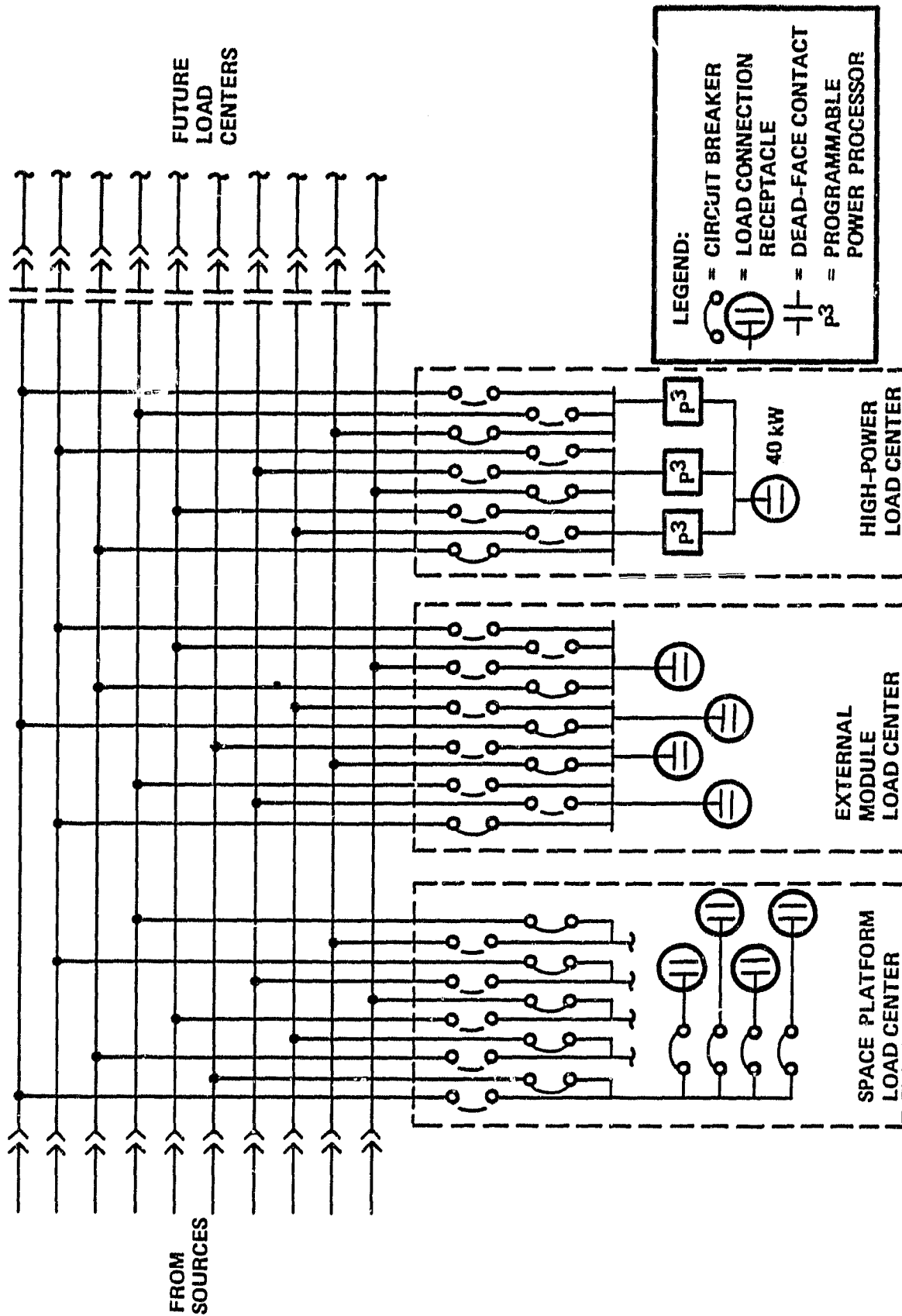


Figure 5-2. Power Distribution Concept

ORIGINAL
OF POWER

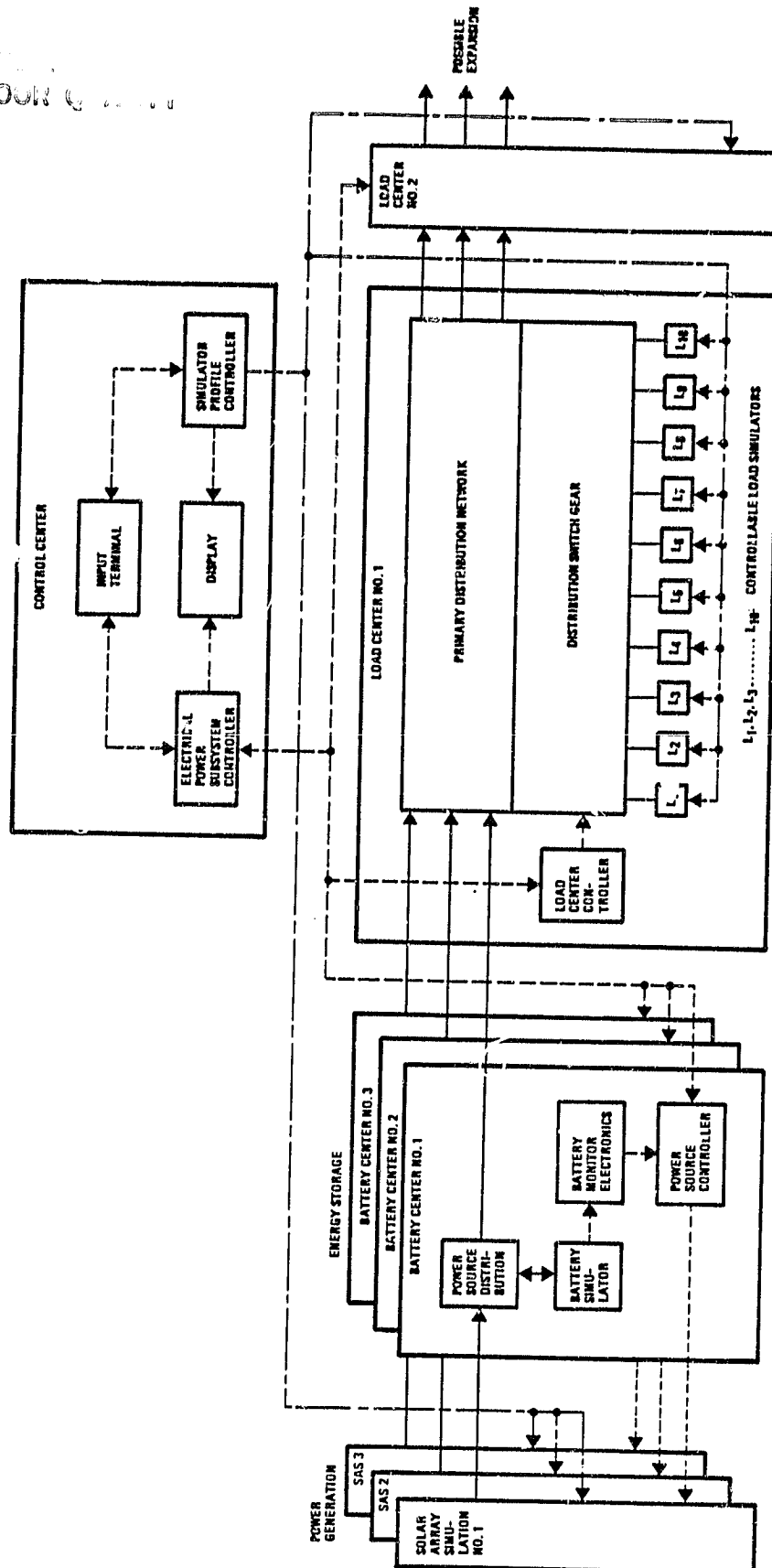


Figure 5-3. Test Facility Concept

Table 5-1. Test Facility Major Item Equipment List

Location	Item	Quantity
Power Generation		1
	Solar Array Simulator	3
Energy Storage		1
	Battery Substitute	3
	Power Source Controller (Includes Battery Monitor Electronics)	3
	Battery Ancillary Panel	3
	Power Supply (Trickle Charger)	3
Load Center		2
	Resistive Loads	9
	Pulse Load Simulator	1
	Switchgear Panels	10
	Load Center Controller	1
Control Center		1
	EPS Controller	1
	Simulation Profile Controller	1
	Video/Keyboard Terminals	2
	Printer	1
	Primary Control Panel	1
	Wall Status Display	1
	Data Recording Equipment	1 set
Subflooring		
	Distribution Wiring	
	Channel Power Transmission Lines	24
	Data Bus Lines	10
	Simulation Control Lines	200
	120 V, 60 Hz Ancillary Power Lines	30
	440 V, 3 phase, 60 Hz, Y-connected, 100 KVA Lines	12

Simulation Profile Controller. In addition, display panels, similar to utility generation station status panels, are included to display the continuing status of the electrical power system.

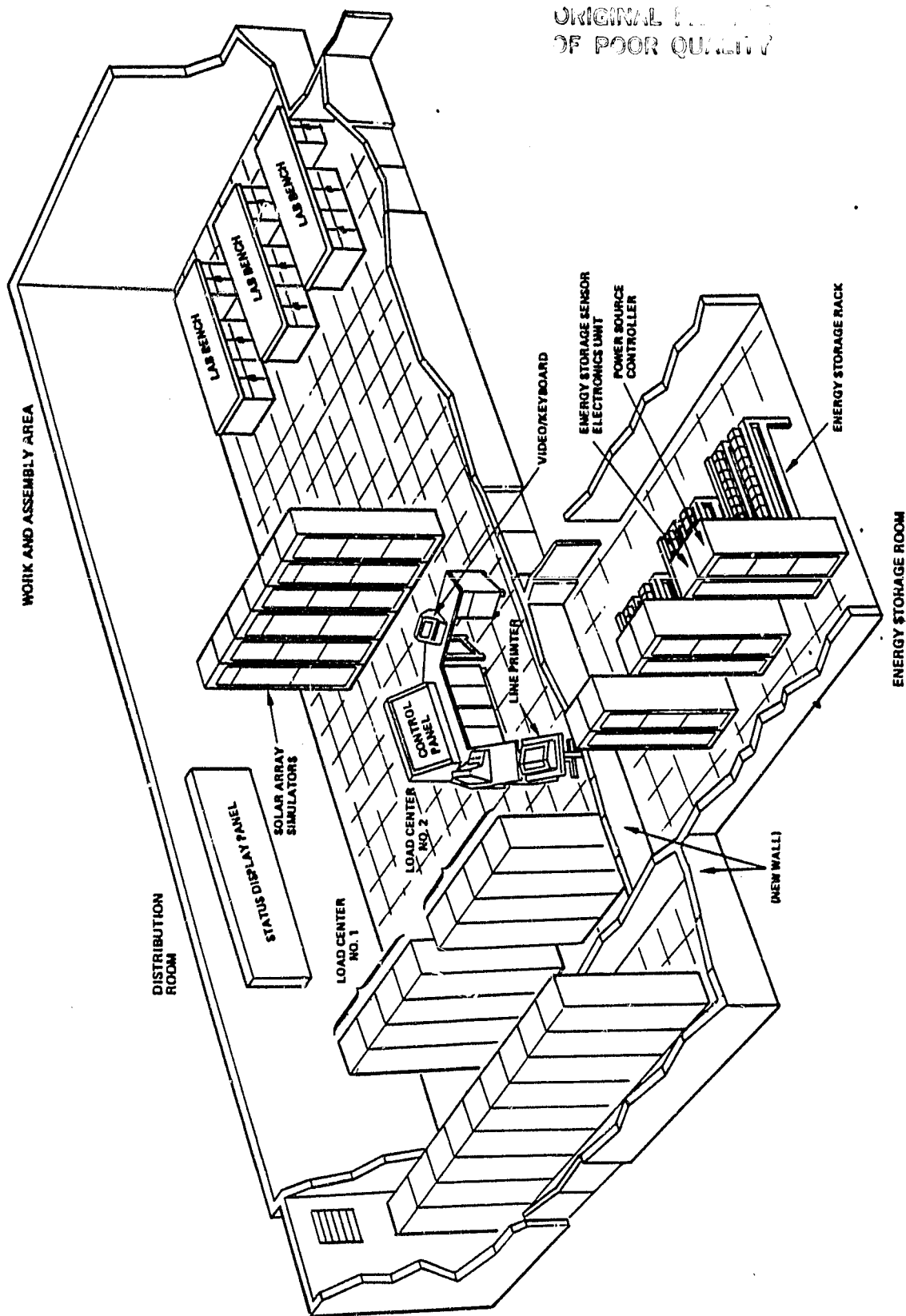
The Test Facility is arranged into two major rooms (Figure 5-4) a distribution room and a energy storage room. The energy storage room is isolated due to ventilation requirements for safe control of any hydrogen gas evolved from the batteries. The energy storage room contains the battery cells, the power source controllers and their associated battery monitor electronics, and the battery ancillary panels. The solar array simulators, load centers, and control equipment are located in the distribution room. Resistive elements of the loads are located just exterior to the distribution room to minimize the cooling and air circulation requirements imposed upon the climate/environmental control system of the building.

5.3 SOLAR ARRAY SIMULATION

Three solar array simulators (Figure 5-5) serve as the power source for the Test Facility. The solar array simulators transform the three-phase 60-cycle commercial utility power into the direct-current output of a solar array and its power processor (a solar array switching unit). The voltage and direct current output of each solar array simulator is independently controlled by the simulation profile controller and the respective power source controller (Figure 5-3). The simulation profile controller provides programming of the output voltage characteristic of each solar array simulator to simulate the effects of array temperature variations, sunlight/eclipse durations, and degradation. The respective power source controller provides the programming to set the level of output current of its solar array simulator to produce the proper level of battery charging current. This approach simulates the functional control of the solar array output by the solar array switching unit in the reference electrical power system configuration (Figure 5-1.)

5.4 BATTERY CENTERS

The battery centers (Figure 5-6) provide the energy storage for eclipse operation and include the battery monitor electronics (cell scanner and temperature) and power source controller. Energy storage is provided by three batteries, each consisting of 160, series-connected,



ORIGINAL PLAN
OF POOR QUALITY

Figure 5-4. Test Facility Physical Layout

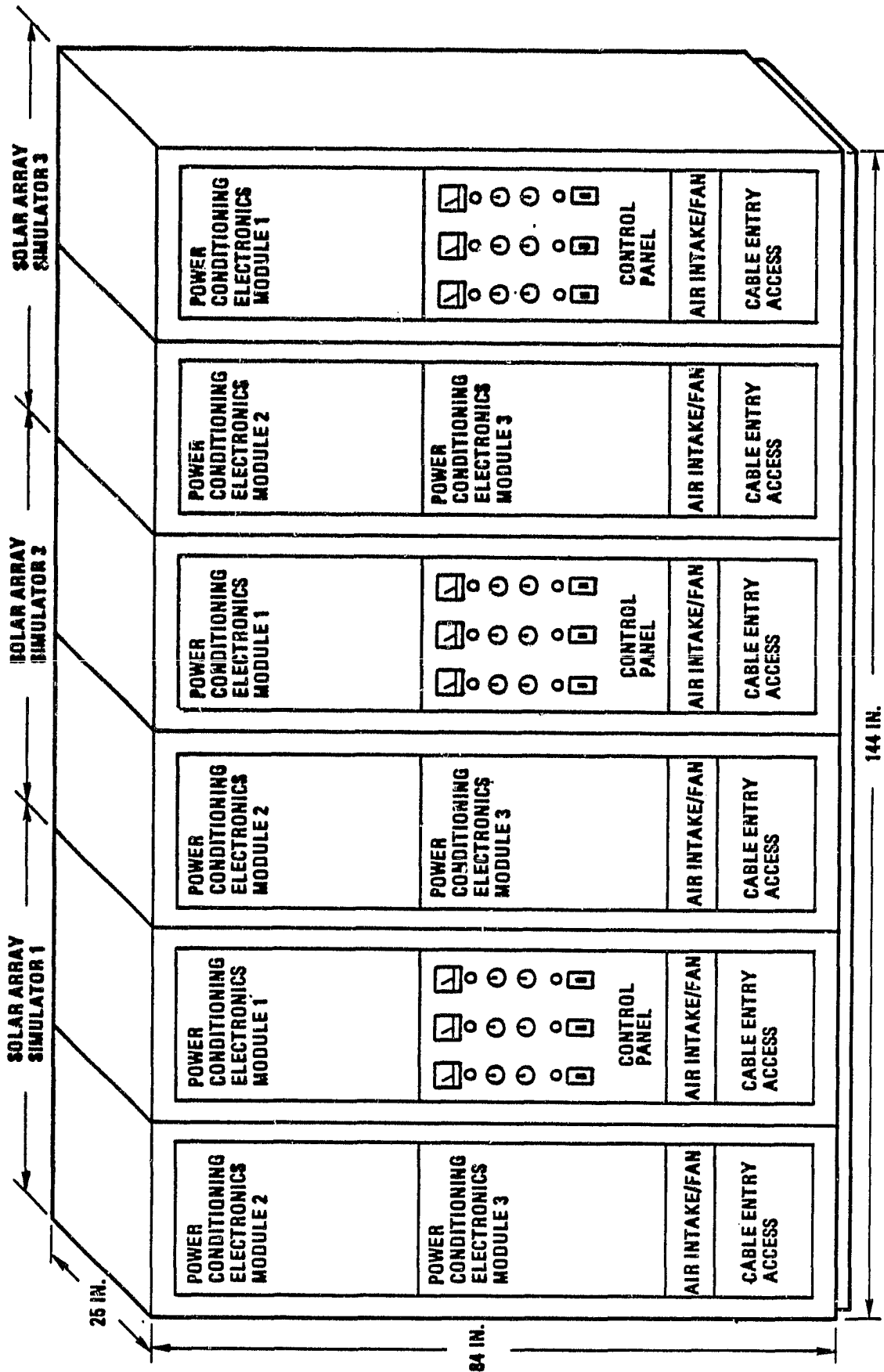


Figure 5-5. Solar Array Simulator Racks

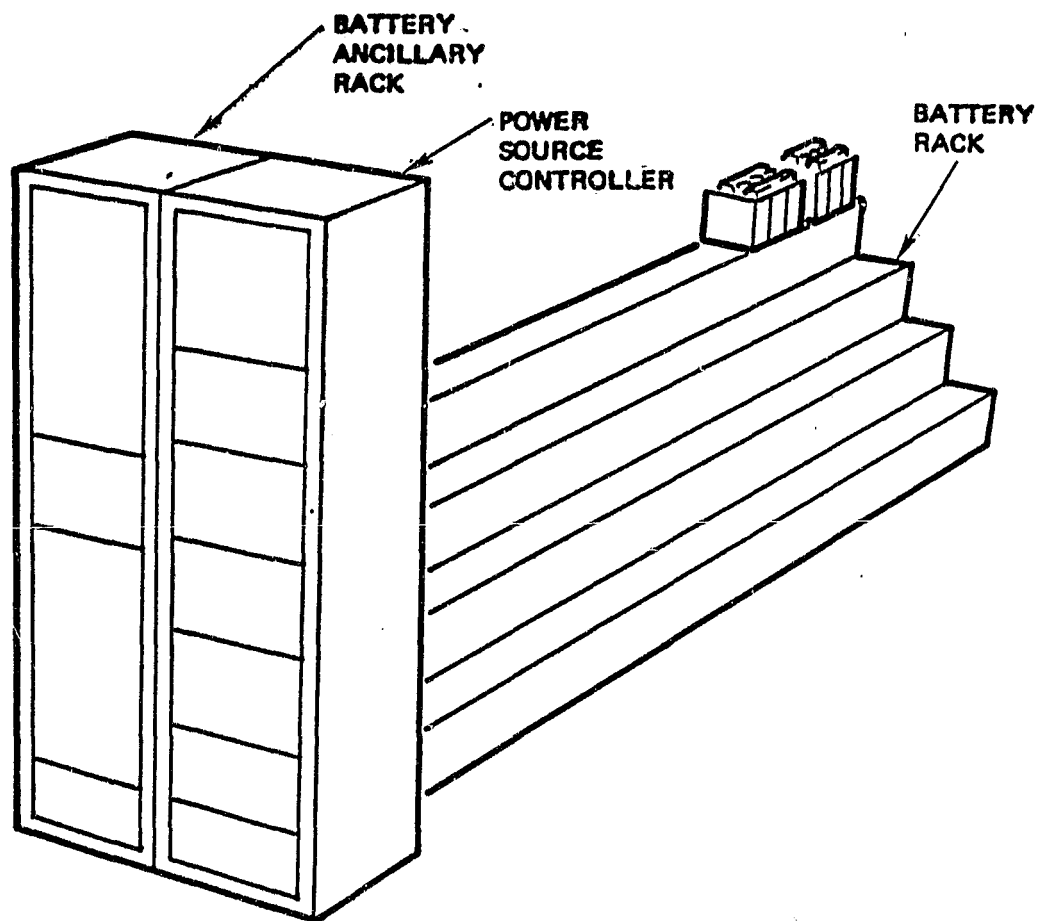


Figure 5-6. Battery Centers

commercial, nickel-cadmium cells. Nickel-cadmium cells are substituted for the nickel-hydrogen cells of the reference electrical power system configuration, for economic and availability considerations. The nickel-hydrogen cell electrical output characteristics during discharge will be closely simulated, and the charging characteristics will be reasonably similar. Overcharge and thermal conditions associated with nickel-hydrogen chemistry are not simulated by the commercial, vented, nickel-cadmium cells.

The interconnection of the solar array simulator, battery, and primary output bus occurs in the battery ancillary panel (Figure 5-7). Protection equipment is included for battery fault current interrupt (excessive discharge current). The solar array simulator output is inherently current limited.

The battery requires support functions for direct trickle charge when the facility is inoperative, for reconditioning discharge, and for current monitoring. These battery support functions are also connected at the battery ancillary panel (Figure 5-7).

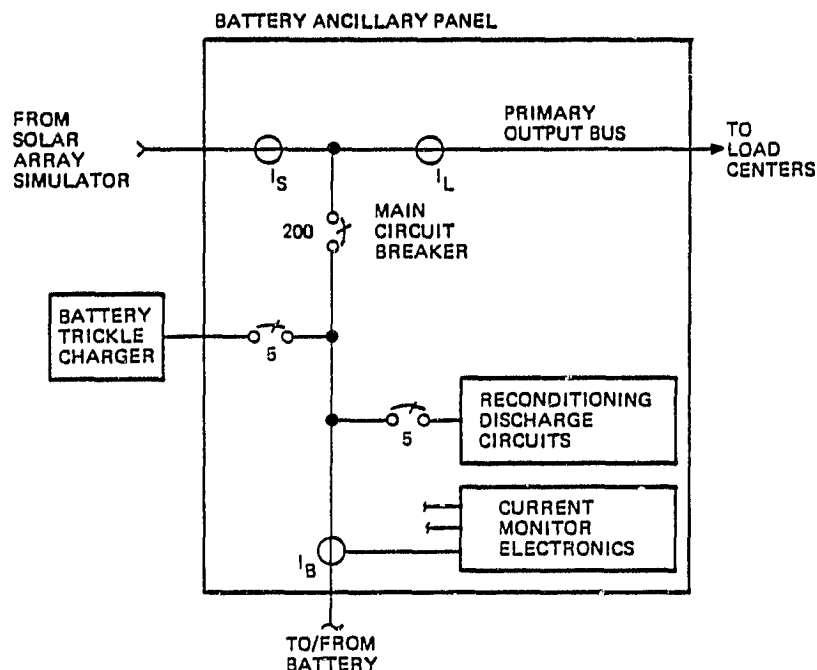


Figure 5-7. Battery and Support Connections

5.5 LOAD CENTERS

Two load centers are defined for the Test Facility to allow simulation of the long transmission line effects between widely separated load centers as on a large space station. Identical load centers are utilized to minimize engineering costs; no advantage is evident in diverse load center designs. The total load capability of both load centers is 48 kilowatts (24 kilowatts in each load center) and can fully load the three 16-kilowatt power channels.

Each load center (Figures 5-8 and 5-9) consists of the primary distribution switchgear, controllable load simulators, the Load Center Controller, and supporting equipment (fans, displays, etc.). The quantity of loads, their power ratings, and the connection availability for each load to the three primary buses are selected to demonstrate the autonomous power management concepts. Each load can be connected to either of two primary buses. Load ratings of 1, 2, and 4 kilowatts (nominally) are selected to provide maximum flexibility for demonstration with a minimum of equipment and cost. In addition, the load simulators are three-step variable to provide simulation of fluctuations in payload power demands:

4 kW: 0, 2.5, 3.25, 4.0 kilowatts

2 kW: 0, 1.5, 1.75, 2.0 kilowatts

1 kW: 0, 0.5, 0.75, 1.0 kilowatts

A three-kilowatt pulsed load simulator is also included in each load center and represents 12.5 percent of the 24-kilowatt capacity. This power level is sufficient to test the facility under pulsating load conditions. The pulse simulator may be connected to any of the three primary buses for versatility in testing.

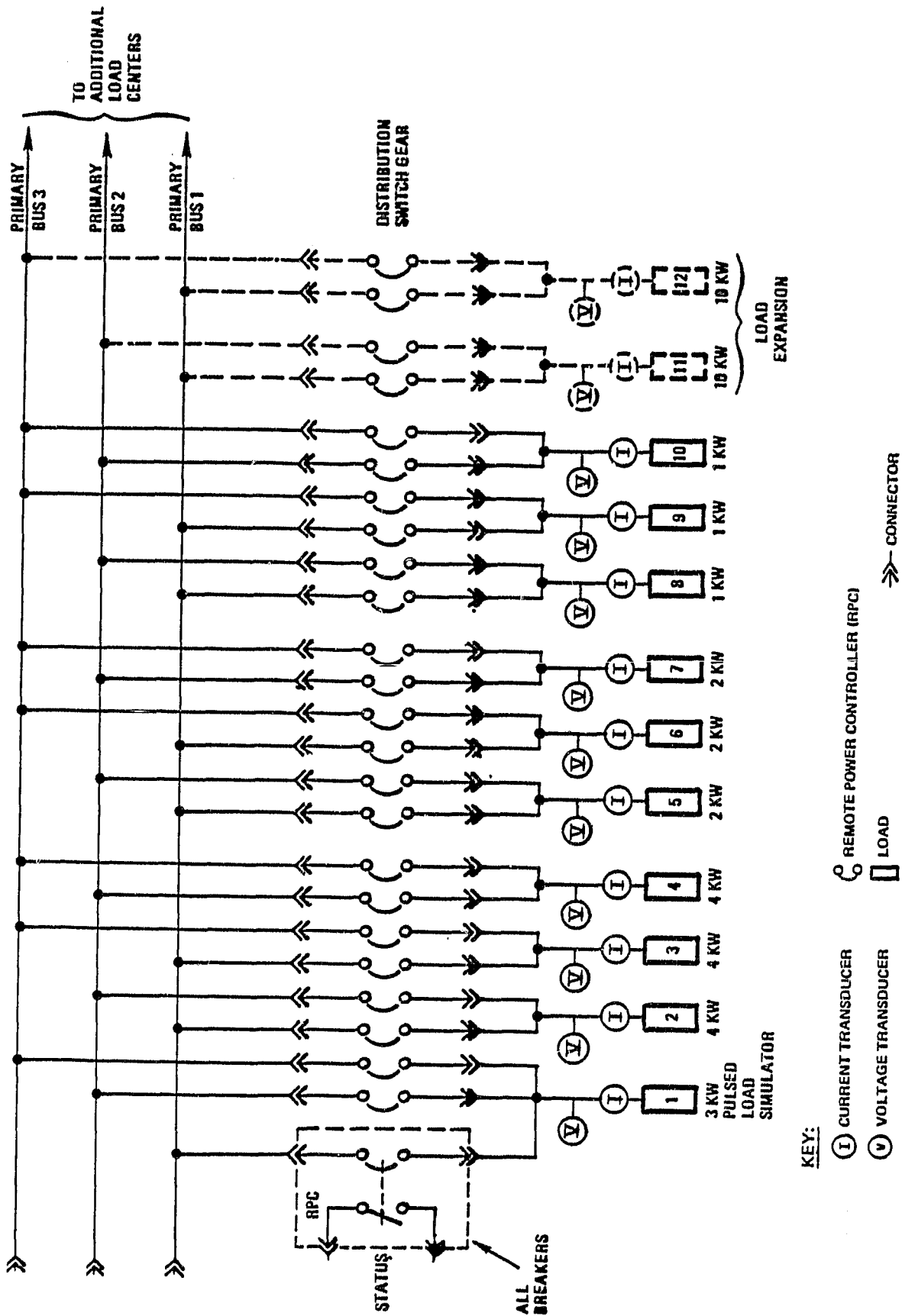


Figure 5-8. Typical Load Center

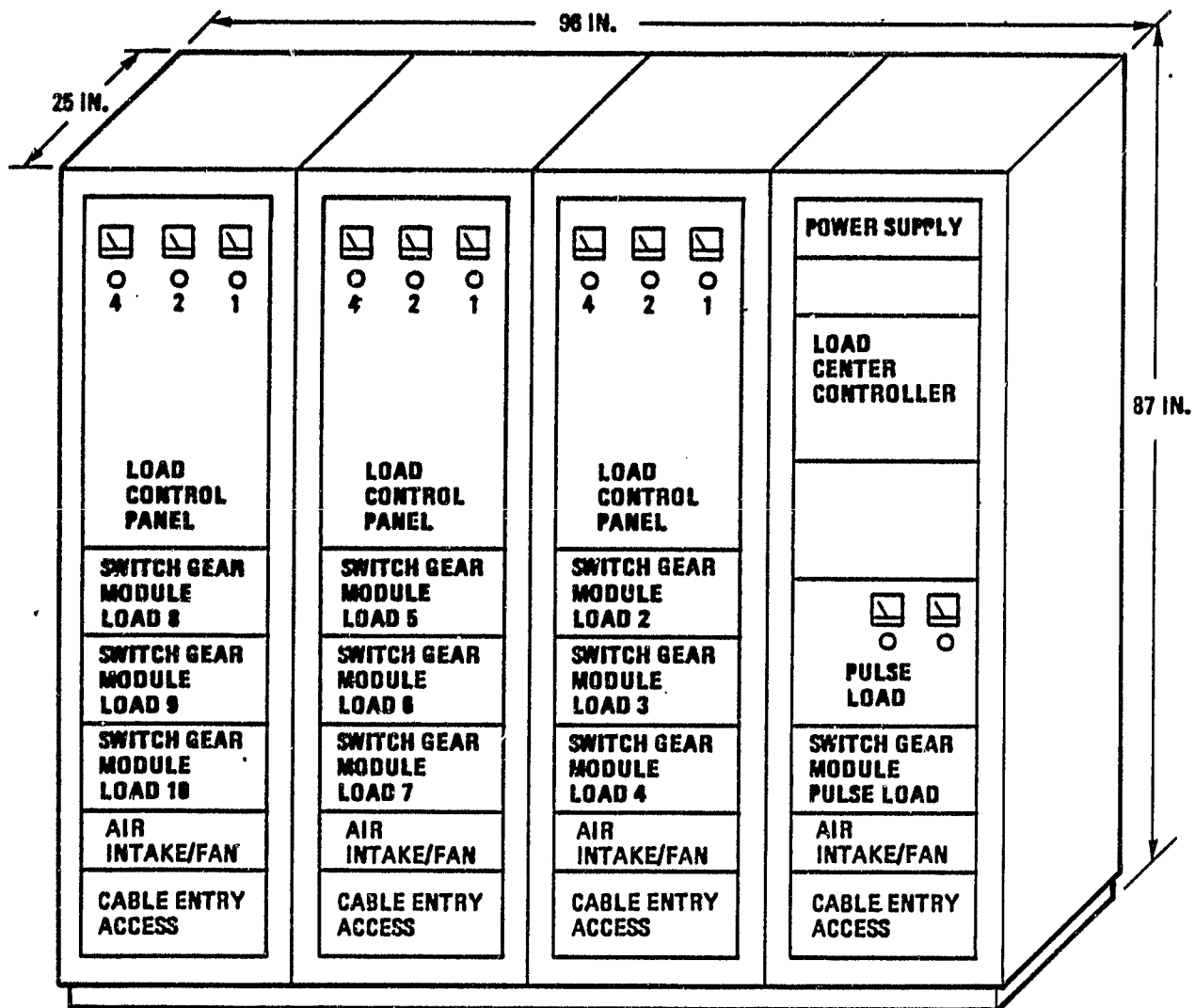


Figure 5-9. Load Center Packaging Concept

5.6 CONTROL AND DISPLAYS

Control of the Test Facility operations resides in the Control Console which is located centrally in the distribution room (Figure 5-10) of the facility. The Control Console contains the primary control panel, the simulation profile controller, the electrical power system controller, the supporting video/keyboard terminals, floppy diskette drives, and power supplies. In addition, auxiliary equipment such as recorders and printers may be included for various operational scenarios.

The simulation profile controller communicates with the electrical power system controller, and it can represent spacecraft controller/computer commands, telemetry commands and data requests, or onboard spacecraft personnel control commands. The simulation profile controller also provides the simulation of solar array eclipse/sunlight cycles, controls the individual load step fluctuations, and selects and initiates anomalies. These actions are programmable, and may constitute an elaborate series of programmable cycles and actions defined on a floppy diskette, or a simple single cycle of operational events initiated manually in real time via the primary control panel.

The primary control panel displays the status of the electrical power system as monitored on the data bus and represents the telemetry data that is available to a ground monitor station. Control switches are also provided to initiate priority commands to the electrical power system via the data bus, again representing telemetry commands from a ground station or commands from spacecraft onboard personnel.

A large wall mounted electrical power system status panel (Figure 5-10) displays the status and pertinent parameters of the electrical power system in real time. This panel is similar to electrical utility status panels incorporated at generation stations and is driven by hardwired analog and discrete signals. A basis for comparison and correlation with the data bus generated status displayed on the primary control panel is thereby provided.

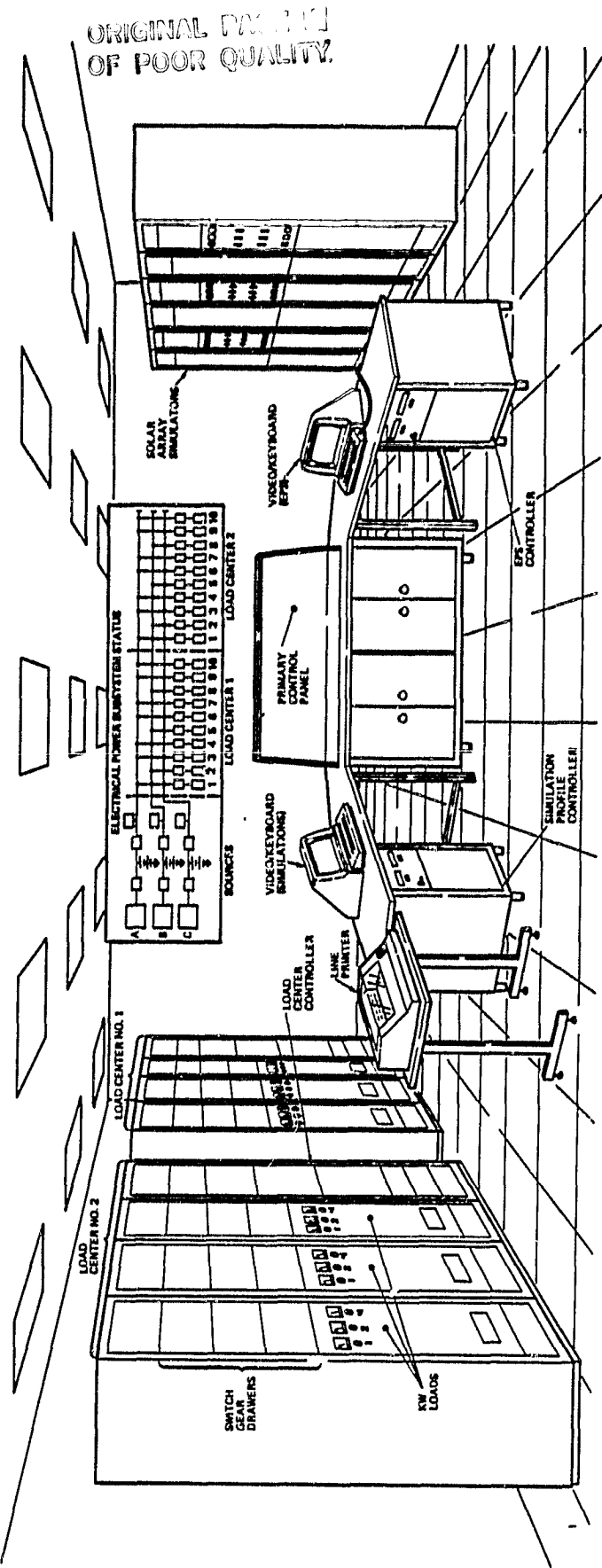


Figure 5-10. Test Facility Operations Are Centered at the Control Console

5.7 FACILITY SUPPORT

The test breadboard components require facility support: a building for protection from the weather, substantial utility electrical power, dissipation of the load center heat, and safety precautions. The installation of the breadboard in a building with adequate electrical power, air conditioning, ventilation, and isolation will suffice. Approximately 1200 square feet of floor area are required. Two-thirds of this floor space is allocated to the solar array simulators, load centers, controls, and displays. Cooling may be by the building air conditioning system. However, an attractive alternative is to locate the resistive elements of the loads external to the building proper and cool these with forced external air flow.

Approximately 400 square feet of the floor space is allocated to an isolated room for the batteries. This room requires forced air ventilation to preclude any accumulation of unsafe mixtures of hydrogen and air (3 percent or greater hydrogen content). The forced ventilation would be initiated prior to, and operated during, Test Facility operation (any battery charging) and battery room access (e.g., electrolyte servicing). The forced ventilation would also be initiated upon detection of hydrogen presence (1 percent or greater hydrogen concentration) by sensors, and the sensors would also initiate an alarm system. In addition, safety procedures for battery access are required to limit, document, and control personnel access. All smoking must be prohibited! Burning or smoldering tobacco will ignite combustible mixtures of hydrogen and air, and the combustion products of tobacco (smoke constituents) often produce false hydrogen sensor alarms. [Hydrogen sensors are typically sensitive to many hydrocarbon compounds as well as gaseous hydrogen.]

5.8 ANOMALY SIMULATION

A repertoire of generic anomalies for the electrical power system (Table 5-2) is included in the Test Facility conceptual design. These anomalies provide the stimuli to exercise the power management control strategies, equipment control laws (algorithms), and autonomous operation to accommodate and/or tolerate (isolate) anomalies. Evaluation of the software for this critical function is thereby implemented.

Table 5-2. Generic EPS Anomalies

Equipment	Failure Mode Simulated	Implementation
Battery	Poor Cell Performance (Low Voltage, Slow Charging)	High Resistance Shunt of Cell
	Shorted Cell*	Low Resistance Shunt of Cell
	Open Cell	Main Circuit Breaker Opened
	Inoperative Cell Monitor	Open Cell Monitor Wire
Switchgear	Faulted Open or Closed	Interrupt command line
	Invalid Status Data	Open Switchgear Monitor Wire Monitor Signal Grounded Monitor Signal Connected to Signal Power
Solar Array	Degraded Output	Reduce Solar Simulator Output Voltage and Current
Primary Bus	Ground Fault*	Apply Short
	Overload	Apply Added Load (10 kW)

*Caution must be exercised in simulating shorted or ground faulted conditions as very high power surges can be attained with the battery capacity supporting each channel.

The anomalies represent the major failure modes of normal electrical power system operation: switchgear, load, and battery problems. Additional anomalies associated with the status monitoring and data gathering from the electrical power system that are required for automated control and management decisions are also included. These anomalies provide the stimuli for ultimately demonstrating validation techniques incorporated within interface hardware and into data acquisition software. The repertoire of anomalies may be expanded in the future as the development of automation technology matures sufficiently to address redundancy requirements and their implementation in software coding, computational and decision processing, and data transfer (data buses).

5.9 OPERATION

The test facility operation is initiated by application of utility power (120-volt, 60-cycle, single-phase) to the various ancillary low voltage power supplies supporting the power management subsystem breadboard controller, the simulation profile controller, and the displays and controls. Initialization of the electrical power system is per the programmed plan of the power management subsystem controllers - preferably pre-programmed to eclipse conditions (no solar array output) and no loads operational. Verification is observable on the primary control panel display and on the electrical power system status panel.

High power operation commences with application of utility power (440-volt, 60-cycle, three-phase) to the solar array simulators followed by closure of the main circuit breakers on the three battery ancillary panels (Figure 5-7). Subsequent operation is predicated upon the data (operational profile) programmed into the simulation profile controller. Solar array conditions (eclipse/sunlight times, degradation level), spacecraft load profile (which loads are to be activated, and when), profile variations of each load, and anomaly selection and introduction are controlled by the programming of the simulation profile controller.

The power management subsystem responds to the subsequent stimuli from the simulation profile controller (representing the spacecraft computer) and operates the electrical power system, in accordance with its preprogrammed control laws (algorithms), to fulfill the load power needs, recharge the batteries, and accommodate anomalies. The power management subsystem responses are observable on the data bus as command and data traffic; the electrical power system responses are displayed by the electrical power system status panel and on the primary control panel.

6. TRADE ANALYSES

The Test Facility requires various hardware simulations or substitutions whenever spacecraft or prototype equipment is not available or appropriate. Two major analyses were undertaken in identifying the most effective approach for Test Facility equipment:

- 1) Selection of the energy storage simulation approach
- 2) Evaluation of dissipation versus regeneration of load power.

A substitution of commercial nickel-cadmium cells for the nickel-hydrogen cells of the energy storage approach in the reference electrical power system was determined to provide excellent performance simulation, to be cost effective, and hence to be the practical approach. Resistive loads were selected because regeneration was not cost effective. These results are incorporated in the definition of the Test Facility.

6.1 ENERGY STORAGE SIMULATION

The energy storage for each channel of the reference electrical power system is a 160-cell, 150-ampere-hour nickel-hydrogen battery. Similar energy storage performance is therefore required for each channel of the Test Facility. However, these 150-ampere-hour nickel-hydrogen cells are not presently available, and extensive development is required to achieve technology readiness by 1986. Consequently, neither spacecraft nor prototype 150-ampere-hour nickel-hydrogen cells are available for application in the Test Facility. Furthermore, to date, nickel-hydrogen cells (50-ampere-hour) are very expensive, and this warrants consideration of more economical alternatives for a Test Facility.

Six approaches, representing these technology disciplines, were identified to provide the requisite energy storage performance (Figure 6-1). Each approach was analyzed for its replication of pertinent nickel-hydrogen performance characteristics, for its procurement cost, and for availability (development status). Commercial nickel-cadmium cells were selected to essentially replace the 150-ampere-hour nickel-hydrogen cells of the reference electrical power system on a one-for-one basis. These commercial nickel-cadmium cells closely simulate the electrical

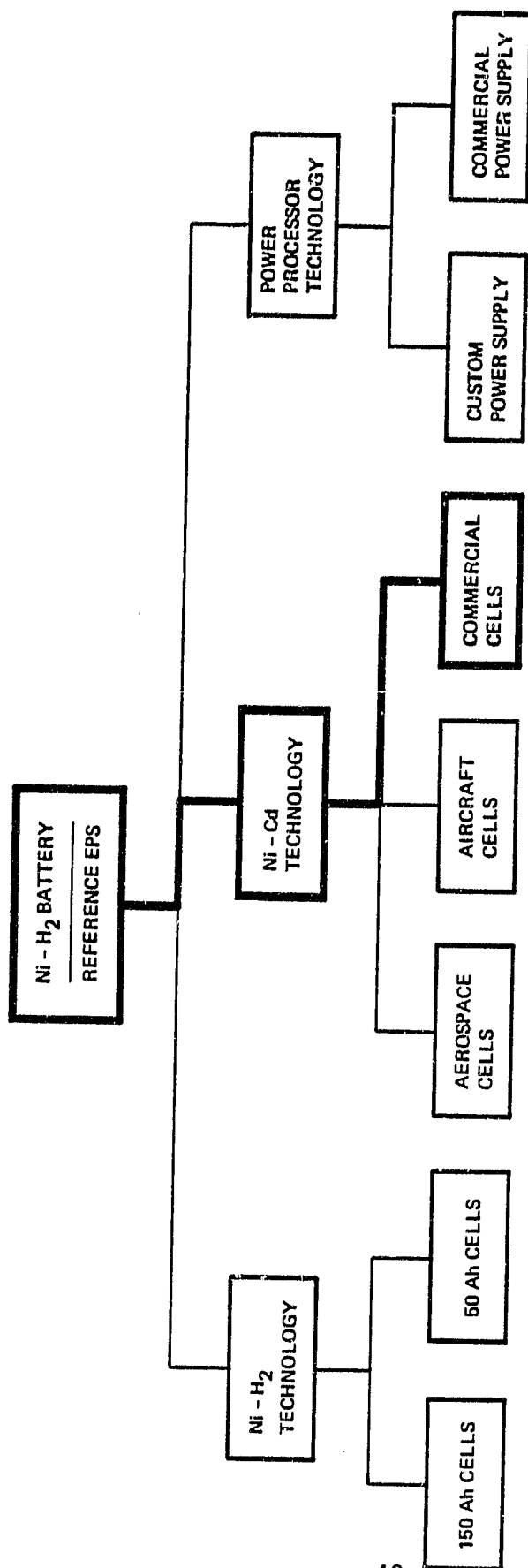


Figure 6-1. Commercial Ni-Cd Selected for Ni-H₂ Simulation

performance of nickel-hydrogen cells during discharge and recharge. Overcharge and thermal conditions, of little relevance to the operation of the Test Facility, are not simulated.

6.1.1 Nickel-Hydrogen Technology

A 150-ampere-hour nickel-hydrogen (Ni-H_2) cell can be simulated by paralleling three of the presently available nickel-hydrogen 50-ampere-hour cells. Electrical characteristics would be nearly identical to a 150-ampere-hour cell since the 150-ampere-hour cell is expected to be essentially a scale-up of the existing 50-ampere-hour cell design. Balanced operation between three parallel cells is the only technical concern, but extrapolation of some experimental data on successfully paralleling two nickel-cadmium cells, wherein excellent operational balance was attained, indicates successful results should be expected for paralleling nickel-hydrogen cells. Occasionally, full discharge (reconditioning) may be required if imbalance reaches a significant level. Hence, acceptable operation for a Test Facility application could be expected. A test is recommended of a 3 by 3 matrix (9 cells) to validate this approach, if selected.

A 160-cell, 150-ampere-hour battery would require 480, 50-ampere-hour cells. Assuming 20 cells for matching and assembly attrition, 500 cells are required for a single battery; 1500 cells for the three-battery facility. However, the 50-ampere-hour cells presently cost approximately \$3000 each. This projects a cell procurement cost of \$4,500,000 for 1500 cells! More economical simulation methods are required. However, as residual or surplus 50- or 150-ampere-hour cells become available from qualification or test programs, they could be allocated to replace simulated batteries and thereby upgrade the Test Facility.

The 50-ampere-hour cell can be utilized to simulate a 150-ampere-hour cell by three scaling methods: 1/3 power, 1/3 energy, 3x depth of discharge. Each method accepts the threefold increase in impedance and the 1/3 fault current capability of this smaller cell. These are tolerable deviations. More significant system operational limitations occur for each method. In addition, the cell procurement cost of \$1,500,000 (500 cells at \$3000/cell) is very expensive for the reduced capability.

Scaling power to $1/3$ produces a channel rating of 5 to 6 kilowatts instead of 16 kilowatts. This smaller channel rating significantly limits the ability of the Test Facility to exercise other system equipment and demonstrate system performance at full equipment ratings. This limitation is particularly significant to switchgear performance, central power processing stability, transient response, and electromagnetic compatibility. Hence, power scaling is contrary to the goals of the Test Facility and should be avoided.

Scaling down the energy to $1/3$ would entail full power operation for $1/3$ the duration. An orbital period becomes 30 minutes with a 12-minute eclipse and 18-minutes of sunlight instead of the normal 90-minute period with a 36-minute eclipse and 54-minutes of sunlight. Operational procedures must be accelerated accordingly. Also, discharge rates (1.5 C), recharge rates (1.0 C), and their associated battery heating would be 3x that of the 150-ampere-hour battery. Thermal stability and repeatability of performance would be expected to suffer. Correction of the data would be required to project performance of the full scale system (i.e., with a 150-ampere-hour battery). Again, such data manipulation requiring scale-up correction factors is contrary to the goals of the Test Facility.

Scaling up the depth of discharge would entail full power operation for the full 90-minutes orbital period (36 minutes of eclipse, 54 minutes of sunlight). This subjects the 50-ampere-hour battery to much greater depth of discharge. The 150-ampere-hour battery is sized for a 30 to 33 percent depth of discharge; a 50-ampere-hour battery would require 90 to 99 percent depth of discharge. This is based upon nameplate ratings; actual capacity is expected to be 110 percent of nameplate.

The 90 to 99 percent depth of discharge implies operating the battery into the "knee" of the polarization curve. Operation of 160 series cells repeatedly into this "knee" is expected to result in rapid dispersion of cell characteristics and to produce significant variation from cycle to cycle of the battery voltage at the end of discharge (end of eclipse). Also, the high rate of charge and discharge would be detrimental to consistent and representative performance due to the heating effects of discharge and overcharge. Hence, this approach would yield a poor correlation

of performance with a full scale (150-ampere-hour) battery. Battery life would be very short and require more frequent replacement at significant added expense.

6.1.2 Nickel-Cadmium Technology

An alternate approach is to simulate the nickel-hydrogen electro-chemistry with nickel-cadmium (Ni-Cd). Nickel-cadmium has very similar charge and discharge characteristics having a polarization characteristic only a few millivolts lower than nickel-hydrogen. A nickel-cadmium battery would closely simulate the electrical performance of a nickel-hydrogen battery of the same capacity (ampere-hour rating), except during overcharge.

Three nickel-hydrogen discharge characteristics are considered in the selection of a nickel-cadmium cell:

- a) The slope of the discharge characteristic curve
- b) End of discharge voltage
- c) Transient response.

The simulation approach can be described in terms of the discharge characteristic curve shown in Figure 6-2. The slope of the AB segment (Figure 6-2) is a function of cell internal impedance, discharge current, and cell capacity. Nickel-cadmium cells have higher internal impedance than nickel-hydrogen cells and, at comparable discharge rates and cell capacity, exhibit steeper regulation slopes. However, the slope can be adjusted by judiciously selecting the cell capacity and operating range (incremental depth of discharge) to attain a reasonable simulation of the nickel-hydrogen cell.

The end-of-discharge voltage is represented by point B of Figure 6-2. The capacity discharged during battery cycling is represented by the length of the segment AB (Figure 6-2). This segment can be moved (right or left in Figure 6-2) by operational choice until B is the desired battery end of discharge voltage for nickel-hydrogen performance.

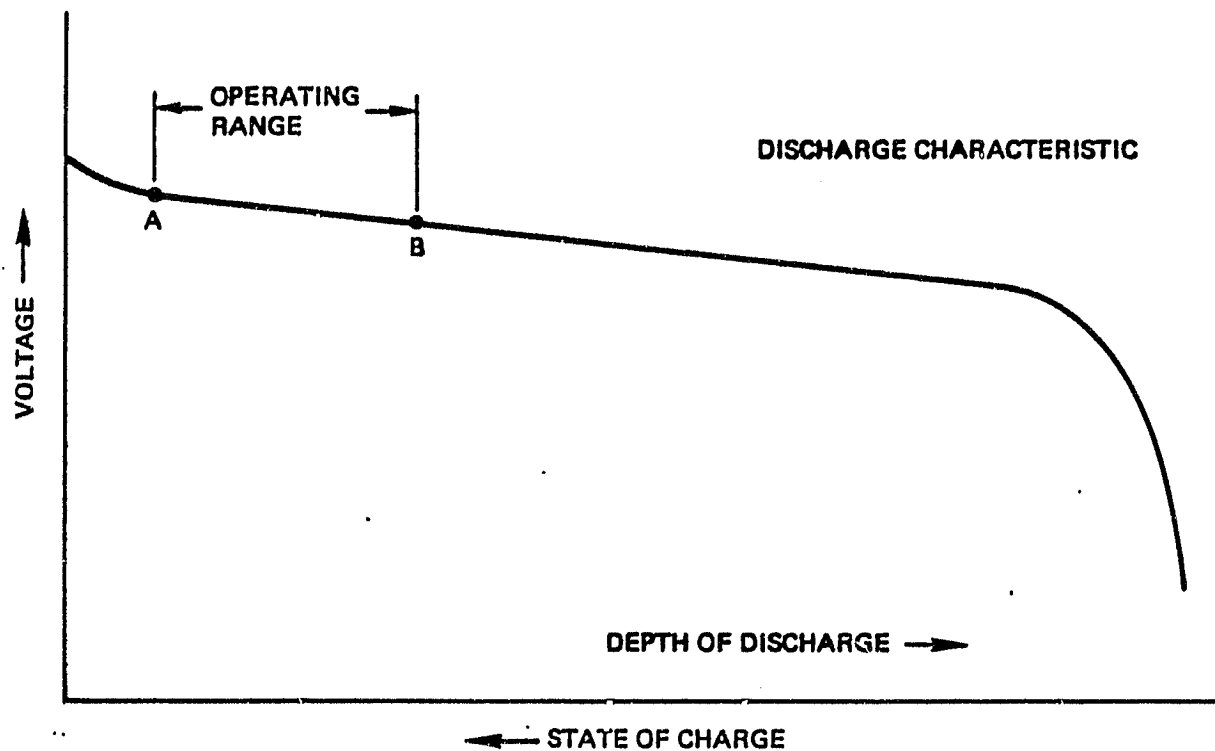


Figure 6-2. Operating Range Selected to Match Nickel-Hydrogen Performance

Overcharging produces oxygen gas in both nickel-hydrogen and nickel-cadmium cells. In the nickel-hydrogen cell, the oxygen immediately combines with the hydrogen at any catalytic surface, and rapid heating occurs. In sealed nickel-cadmium cells, oxygen generation increases the cell pressure significantly and eventually recombines at the cadmium electrode for deferred heating. In vented nickel-cadmium cells, oxygen and hydrogen are generated and expelled to the environment, and major heating is avoided. However, water must be added to the cell to maintain proper electrolyte concentration. Overcharging occurs for only 3 to 5 minutes of the 90 minute orbital period for a fully loaded electrical system (16 kilowatts/channel). However, under a light load, a large portion of the 54-minute sunlight (charging) duration is overcharge. This affects primarily the battery charging algorithm by requiring reduced charge current (lower bus voltage) during this time. However, system operation is several volts

higher during overcharge with nickel-cadmium instead of nickel-hydrogen batteries. This is considered a minor deviation and acceptable in order to attain an economical simulation of nickel-hydrogen batteries.

Transient characteristics of both nickel-hydrogen and nickel-cadmium cells are not well defined. Differences in transient response are expected due to the various methods of electrode construction for nickel-cadmium plates and the hydrogen (gaseous) electrode of the nickel-hydrogen cell. A testing program to define transient response is recommended to evaluate the degree of similarity to nickel-hydrogen to be attained with the various nickel-cadmium constructions. However, the nickel-cadmium cell selected to simulate nickel-hydrogen performance should be a high-rate cell with the largest plate surface area available at the chosen capacity. This cell design will provide the best transient performance approximation available with this approach to simulation.

Three distinct types of nickel-cadmium cells are presently produced: spacecraft, aircraft, and commercial. Each type has a different combination of cell case design, plate construction, separator material, and electrolyte quantity. The result is a greatly varying cost but more subtle differences in electrical characteristics.

6.1.2.1 Spacecraft Nickel-Cadmium Cell

Spacecraft nickel-cadmium cell design utilizes hermetically sealed stainless-steel cases, sintered plates, nylon separators, and a starved electrolyte (potassium hydroxide, KOH) system. The cells are designed for high rate discharge and zero-gravity, space-vacuum environment. These cells are a good electrical simulation of nickel-hydrogen cells, having polarization characteristics approximately 30 to 50 millivolts lower than nickel-hydrogen cells except during overcharge. However, cell capacity is limited to 50 ampere-hours for readily available cells. Hence, paralleling of three, 50-ampere-hour nickel-cadmium cells is necessary to simulate one 150-ampere-hour nickel-hydrogen cell. Also, these cells are expensive, approximately \$1200 each (catalog price) and yield a procurement cost of \$1,800,000 for the 1500 cells required to simulate three 160-cell, 150-ampere-hour, nickel-hydrogen batteries. These cells are available from General Electric.

6.1.2.2 Aircraft Nickel-Cadmium Cell

Aircraft nickel-cadmium cell designs for the DC-10 and L-1011 aircraft utilize pressure-vented plastic cases, sintered plates, cellophane separators, and a flooded electrolyte (KOH) system. These cells are designed for high-rate discharge for aircraft auxiliary power unit starting and emergency electrical power. As such, these cells operate essentially upright in a one-g gravitational field, and with significant atmospheric pressure variations (0 to 40,000 feet). These cells are a good electrical simulation of nickel-hydrogen cells, having a polarization characteristic only a few millivolts lower than nickel-hydrogen cells, except during overcharge. On overcharge, these nickel-cadmium cells generate oxygen and hydrogen. However, the cell case design allows venting of these gases. Hence, no recombination and the associated heating occur. Water must be added to make up the oxygen and hydrogen losses. Cell capacity is limited to the present 50-ampere-hour design for immediate availability. Hence, paralleling of three 50-ampere-hour nickel-cadmium cells is necessary to simulate one 150-ampere-hour nickel-hydrogen cell. These nickel-cadmium cells are relatively inexpensive, \$85 each in quantity, and yield a procurement cost of \$127,500 for the 1500 cells required to simulate three 160-cell, 150-ampere-hour, nickel-hydrogen batteries. These cells are available from General Electric and SAFT-America.

6.1.2.3 Commercial Nickel-Cadmium Cell

Commercial nickel-cadmium cell designs utilize vented plastic cases, pocket plate construction, cellophane separators, and a flooded electrolyte (KOH) system. These cells are typically designed for gasoline or diesel engine starting and terrestrial environment (upright orientation, 0 to 12,000 feet altitude and atmospheric pressure), are available in large cell capacities (up to 1300-ampere-hours), and are relatively cheap, \$90 for 200 ampere-hours, \$165 for 400 ampere-hours. However, these cells have higher internal resistance due to the pocket construction of the plates and, hence, a lower polarization characteristic for a given ampere-hour capacity than the aerospace nickel-cadmium cells. However, by judiciously choosing a higher capacity cell, for example the 200-ampere-hour commercial nickel-cadmium cell, a 150-ampere-hour nickel-hydrogen cell can be electrically simulated very well, except during overcharge. Procurement costs

are \$45,000 for the 500 cells required to simulate three 160-cell, 150-ampere-hour nickel-hydrogen batteries. These cells are available from NIFE, SAFT-Canada, and McGraw Edison.

6.1.3 Power Processor Technology

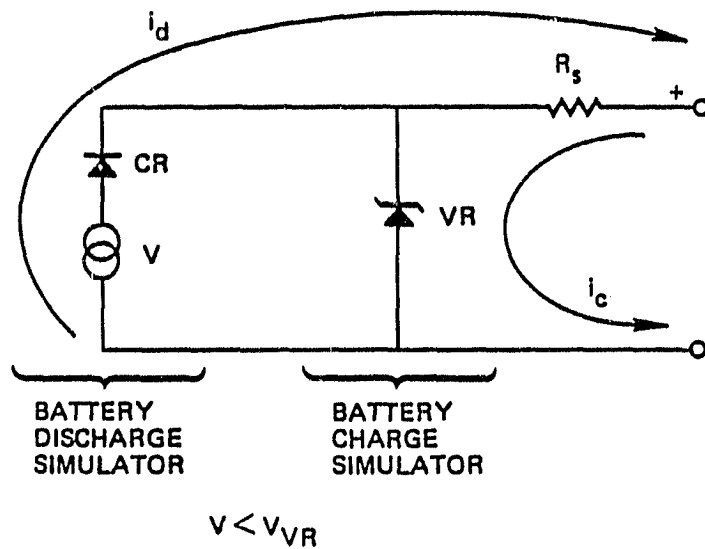
A battery may be simulated by a combination of an electronic power supply and a shunt regulator (Figure 6-3). The electronic power supply produces the battery output power simulating the discharge performance of the battery. The shunt regulator absorbs the input energy delivered to the battery during sunlight (recharge period) and simulates the electrical performance parameters of the battery during recharge.

The electronic power supply is a typical commercial power supply combining these basic functions: transformer, rectifier, and regulator. The regulator is the critical element and requires specific attention to approach the very low static and dynamic impedance characteristics of a nickel-hydrogen battery. Very low ripple and excellent transient response (no overshoot) are needed to represent a nickel-hydrogen battery.

The shunt regulator consists of regulation and dissipation elements (Figure 6-3). The critical element is the regulator which must not admit current when the voltage is low indicating discharge of the battery. Also, the regulator requires a current monitor and an ampere-hour integrator. Proper simulation of the battery voltage during charge depends upon the instantaneous rate of charge (current) and the battery state of charge (ampere-hour integration).

Each channel of the Test Facility is rated at 16 kilowatts. During discharge, 80 amperes must be produced at 200 volts with very little ripple. During recharge 70 amperes must be absorbed with the voltage rising to 240 volts. These are nominal, or rated, values. Peak capabilities of a nickel-hydrogen battery are in excess of ten times more discharge current capability. During recharging the battery is required to absorb approximately 20 percent more current (84 amperes) from a cold solar array (post eclipse) to clamp the array output voltage. Hence, very large capacity electronic equipment is required to simulate battery electrical performance, or a compromise must be accepted in the range of parameter simulation.

a) EQUIVALENT ELECTRONIC SIMULATION OF BATTERY



b) PRACTICAL COMPONENTS

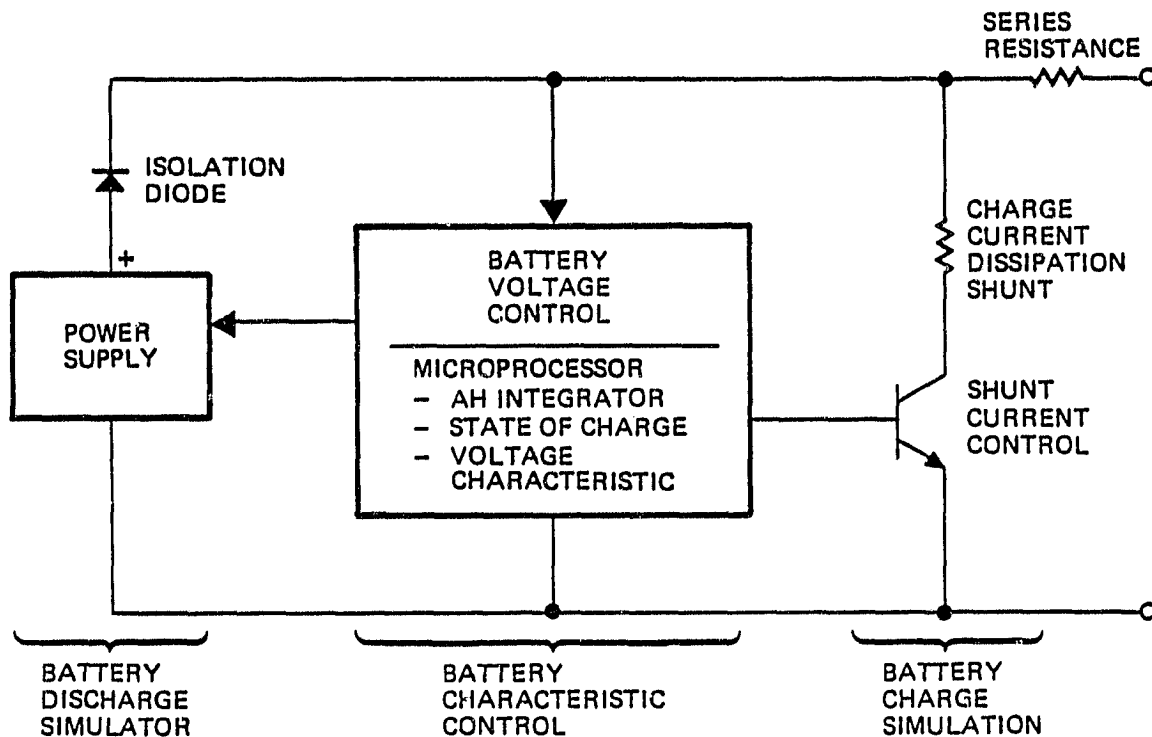


Figure 6-3. Electronic Simulation of Battery

Direct current power supplies cost as little as \$20,000 for 50 kilowatt units. However, these units do not provide the adequately low ripple needed to simulate a battery. A custom designed or modified electronic power supply and shunt regulator to simulate a battery is estimated to cost approximately \$70,000 for each 16 kilowatt unit, with low ripple but with little or no incremental peak power capability. In addition, engineering, development, and packaging design effort is estimated at \$100,000. Hence, this approach is expected to cost over \$300,000 for the three channel Test Facility.

6.2 DISSIPATIVE VERSUS REGENERATIVE LOADS

The two load centers aggregate 48 kilowatts of power. An option exists to pump the power of these loads back into the facility alternating current (60 hertz) utility source (regeneration) rather than dissipate this power as heat with resistive load elements. This regenerative approach has attractive conservation and environmental connotations. However, the economics of the regeneration option are poor, and the resistance load bank approach is therefore recommended.

6.2.1 Resistive Load Bank

The proposed resistive loads aggregate 21 kilowatts per load center arranged as nine loads (Figure 5-8). Each load has three controllable power steps. This load step feature allows simulation of fluctuations within an individual load independent of the quantity of loads activated. Such individual load fluctuations (individual load power profile) are hypothesized for actual payload packages connected to a common electrical load port of the load center. Similar resistive, incrementally stepped load banks have been built by Sotcher Measurement of Sunnyvale, California (408/732-9171). Based upon preliminary technical specifications, a set of nine loads, each having three steps and operating with direct current at 220 \pm 30 volts, will cost approximately \$6800 from Sotcher Measurement. This price does not include any mounting racks nor wiring integration into a load center. Two such load banks are required, one for each load center.

6.2.2 Inverter Load

Nine, 60 hertz, independent inverters are required to provide the same power channel loading assignment options as the nine resistive loads:

Three four kilowatt inverters

Three two kilowatt inverters

Three one kilowatt inverters.

In addition, these inverters require synchronization to the 60 hertz utility power. Several 60 hertz inverter sources were identified and contacted:

Abacus Controls of Somerville, New Jersey

Nova Industries of Nutley, New Jersey

Teledyne-Inet of Lomita, California

The inverter data and quotations from Abacus Controls were the most appropriate and yield a procurement cost of \$92,000 (two load centers at \$46,000 each):

Three one kilowatt units at \$2800	=	\$ 8,400
Three two kilowatt units at \$3600	=	10,800
Three four kilowatt units at \$7500	=	22,500
Synchronizing line ties	=	4,300
		<hr/>
Inverter procurement per load center	=	\$46,000

These inverters represent constant power loads rather than resistive loads. The efficiencies of the inverters approximate 90 percent, and return 38 of the 42 kilowatts at full load operation:

$(3 \text{ units} \times 1 \text{ kW}) + (3 \text{ units} \times 2 \text{ kW}) + 3 \text{ units} \times 4 \text{ kW} = 21 \text{ kW load}$

$21 \text{ kW/load center} \times 2 \text{ load centers} \times 90\% \text{ eff} = 38 \text{ kW power return}$

6.2.3 Economics

The inverter equipment for the regenerative option is considerably more expensive than the resistive load banks: \$92,000 versus \$13,600, a \$78,400 difference. This increased initial cost may ultimately be offset by the savings in energy costs. However, the projected payback periods are lengthy (Figure 6-4):

- a) 6+ years for full-time full-load usage
(24 hours/day, 365 day/year)
- b) 18+ years for eight hours/day usage
(365 days/year)
- c) 26+ years for 40 hours/week
50 weeks/year usage.

For nominal usage, the payback period is expected to exceed 26 years. This period is longer than the projected life of the facility. Hence, this inverter option is rejected in favor of the resistive load bank.

These payback periods are based upon an energy cost of 3.8 cents/kilowatt-hour, a 90 percent inverter efficiency, and a 42-kilowatt continuous load:

$$\begin{aligned}
 \text{Annual Savings} &= 3.8¢ \times 38 \text{ kW} \times (24 \times 365) = \$12,650 \\
 &= 3.8¢ \times 38 \text{ kW} \times (8 \times 365) = 4,216 \\
 &= 3.8¢ \times 38 \text{ kW} \times (40 \times 50) = 3,004
 \end{aligned}$$

Projecting inflationary increases of 15 percent per year in energy costs yields "bookkeeping" payback periods of approximately 5, 9, and 11 years, respectively (Figure 6-5). These shorter payback periods are misleading, technically false, and invalid for payback evaluation and trade decision criteria because dollars of differing value are summed. However, this "bookkeeping" approach is the customary financial accounting practice in effect today. Even these fictitious payback periods are considered too long to warrant the inverter investment.

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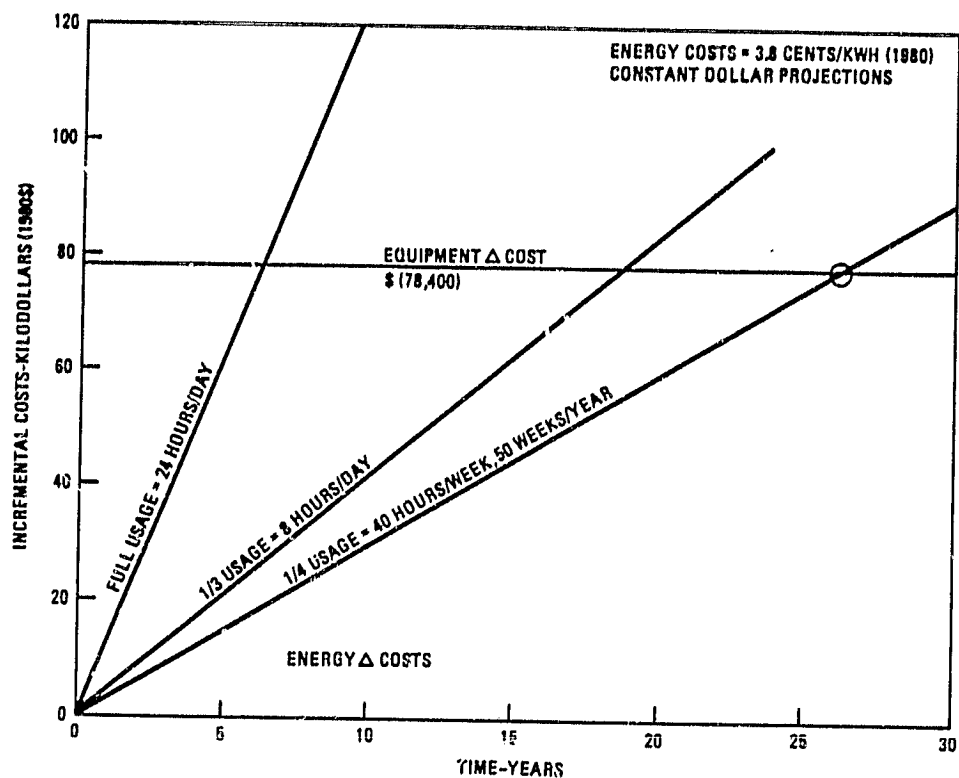


Figure 6-4. Inverter Option Payback Is Too Long

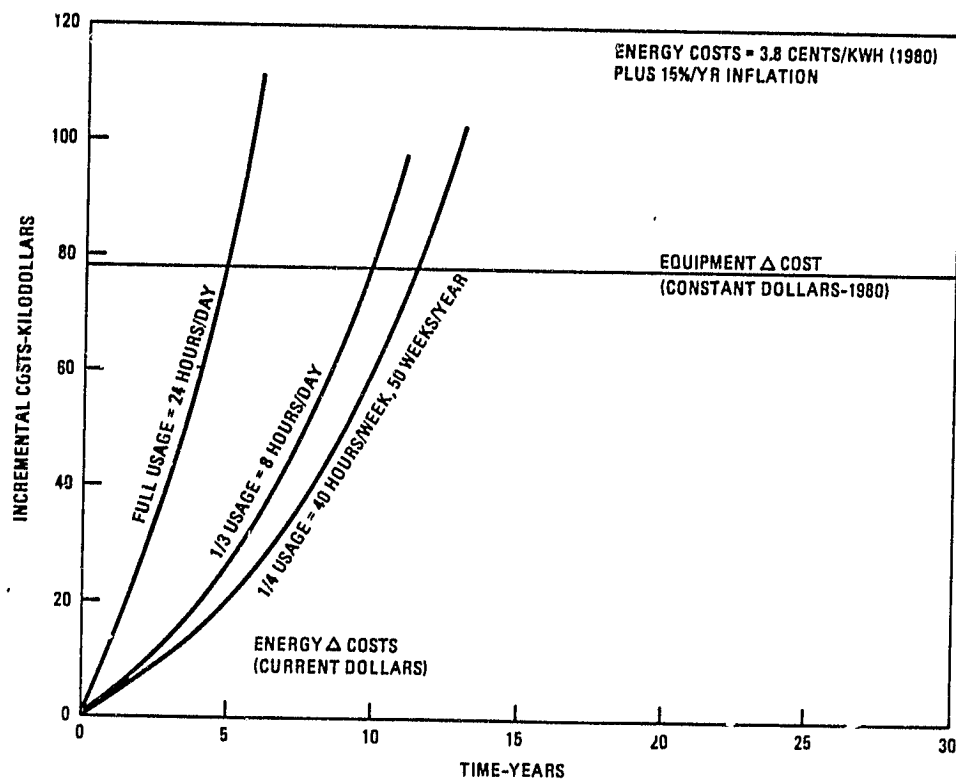


Figure 6-5. Bookkeeping Approach Distorts Trade

7. EQUIPMENT DESCRIPTIONS

7.1 SOLAR ARRAY SIMULATOR

Three Solar Array Simulators (SAS) serve as the power source for the Test Facility. The Solar Array Simulator transforms the three-phase, 60-hertz, commercial utility power into the direct-current output of the solar array and its power processor (solar array switching unit). The voltage and direct current output of each Solar Array Simulator is independently controlled by the Simulation Profile Controller and the respective Power Source Controller (Figure 5-3). The Simulation Profile Controller provides programming of the output voltage characteristic of the Solar Array Simulator to simulate the effects of array temperature variations and sunlight/eclipse durations. The respective Power Source Controller provides the programming to select the level of output current of the Solar Array Simulator to support the loads and to produce the proper level of battery charging current. This approach simulates the functional control of the solar array output by the solar array switching unit (SASU) in conjunction with the Power Source Controller as occurs in the reference electrical power system configuration.

The output power requirements of the Solar Array Simulator are determined by the sum of the channel load rating (16 kilowatts), the charging requirement for the battery, and the losses in power conditioning, control, and distribution equipment. The battery charging power requirement is 14.2 kilowatts:

$$16 \text{ kW} \times \frac{0.6 \text{ hr}}{0.9 \text{ hr}} \times \frac{1.45 \text{ V}}{1.20 \text{ V}} \times 1.1 = 14.2 \text{ kW}$$

where 1.1 = recharge ratio

1.45 = average charge voltage

1.20 = average discharge voltage

0.6 = eclipse duration, hours

0.9 = sunlight duration, hours

The switchgear and circuit protection devices are projected to be greater than 99 percent efficient (0.1 to 0.5 volt drop for mechanical contactors with arc suppressors and 1.1 to 1.7 volt drop for semiconductor switches versus an operating level of 200 to 240 volts), and their losses are negligible. Hence, the Solar Array Simulator must provide 30.2 kilowatts: 16 kilowatts direct to the load, plus 14.2 kilowatts for battery charging.

A photovoltaic array performs similarly to a voltage limited, constant current power supply. Figure 7-1 shows a family of current-voltage (I-V) characteristics for an array under different illumination levels (L_0 through $6 L_0$) and constant temperature. Although the I-V characteristics vary considerably with cell illumination, the voltage at the maximum power points remains relatively constant. However, the characteristics are also very sensitive to cell temperature. The open circuit voltage decreases

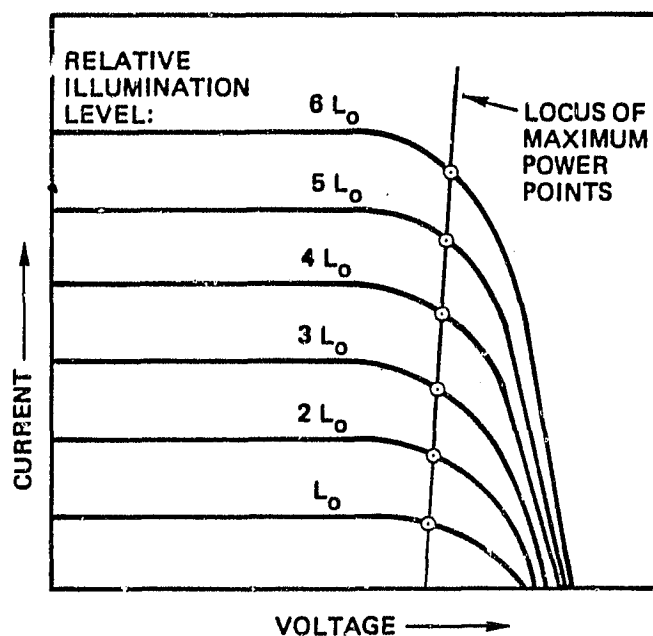


Figure 7-1. Family of Current-Voltage Characteristics for a Photovoltaic Array at Constant Cell Temperature under Different Illumination Levels

with increasing cell temperature at a rate approximately equal to $2 \text{ mV}/^{\circ}\text{C}$ times the number of series cells making up the array. A device built to simulate a photovoltaic array must therefore be able to vary its open-circuit voltage over a considerable range to simulate the effects of cell temperature changes. Also, short-circuit current must be variable to simulate the effects of shadowing and eclipse conditions, and array degradation.

The proposed Solar Array Simulator for the AMPS Test Facility is assembled utilizing the Abacus Controls Incorporated (Somerville, NJ) 11-kilowatt Solar Array Simulator. This unit combines a high-efficiency switching regulator, a high-performance series regulator, and a low-power adjustable analog I-V generator (Figure 7-2) to simulate the static and dynamic electrical characteristics of photovoltaic cells operated in multiple series/parallel combinations (a solar array). This design approach has been built and extensively tested for an 11-kilowatt unit.*

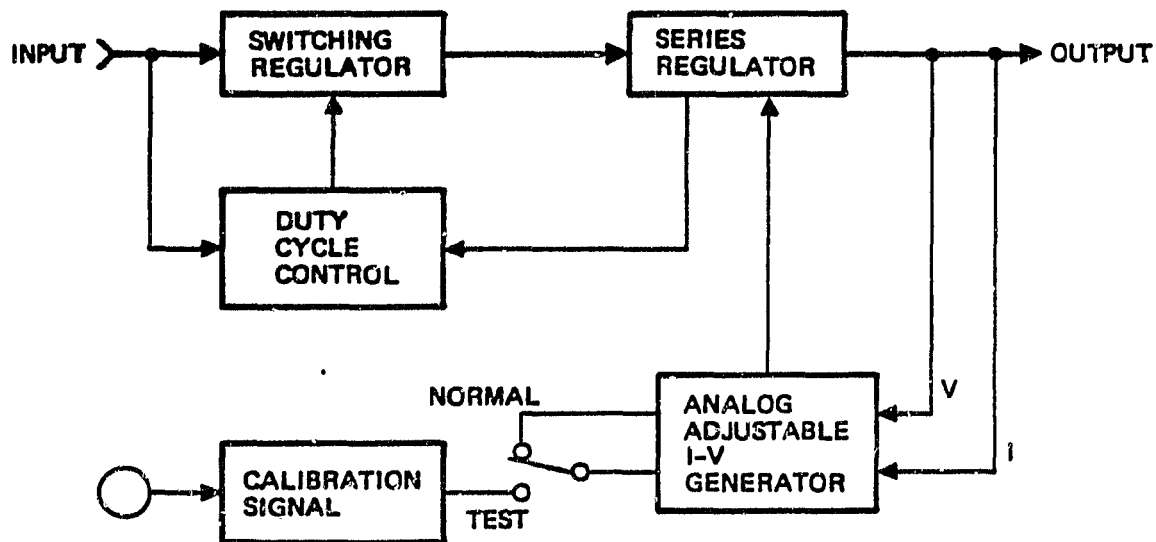


Figure 7-2. Analog I-V Power Control

*D. R. Smith, G. A. O'Sullivan, and F. K. O'Sullivan, "The Design and Performance of an 11-kW Solar Array Simulator." IEEE paper CH1529-7/80/0000-0220.

In addition to generating the I-V characteristic of a solar array, this simulator also reproduces the solar array dynamic characteristics while operating into a variety of reactive loads. For the Test Facility, three of these 11-kilowatt units are connected and operated in parallel to produce the 33-kilowatt Solar Array Simulator (Figure 7-3). Three of these 33-kilowatt units are required for the Test Facility, one per power channel. These units require six 24- by 30- by 84-inch electronic racks to house this equipment (Figure 5-5).

Table 7-1. Solar Array Simulator Specifications

Electrical:

Input: 42 kW at 440 volts, 3-phase (delta), 60 hertz

Output power: 33 kW at 200 Vdc

Efficiency: 80 percent

Adjustable open circuit voltage: 175 to 375 volts

Adjustable short circuit current: 0 to 150 amperes

Variation in the effect on the equivalent shunt resistance of the I-V output characteristic (Figure 7-4) such that the ratio of the voltage at the peak power point to the open circuit voltage can be adjusted over a range of 0.65 to 0.85:

$$\frac{\text{Peak Power Voltage}}{\text{Open Circuit Voltage}} = \frac{V_{pp}}{V_{oc}} = 0.65 \text{ to } 0.85$$

Variation in the effect on the equivalent series resistance of the I-V output characteristic (Figure 7-3) such that the ratio of the current at the peak power point to the short circuit current can be adjusted over a range of 0.70 to 0.90:

$$\frac{\text{Peak Power Current}}{\text{Short Circuit Current}} = \frac{I_{pp}}{I_{sc}} = 0.70 \text{ to } 0.90$$

Dimensions: Two racks (30 x 24 x 84 inches) per 33-kW unit

Thermal: Maximum dissipated power = 9 kW

Cooling fans will be used to bring in air at the bottom and blow it out the top. Fan power required: 120 Vac, 1 phase, 60 hertz

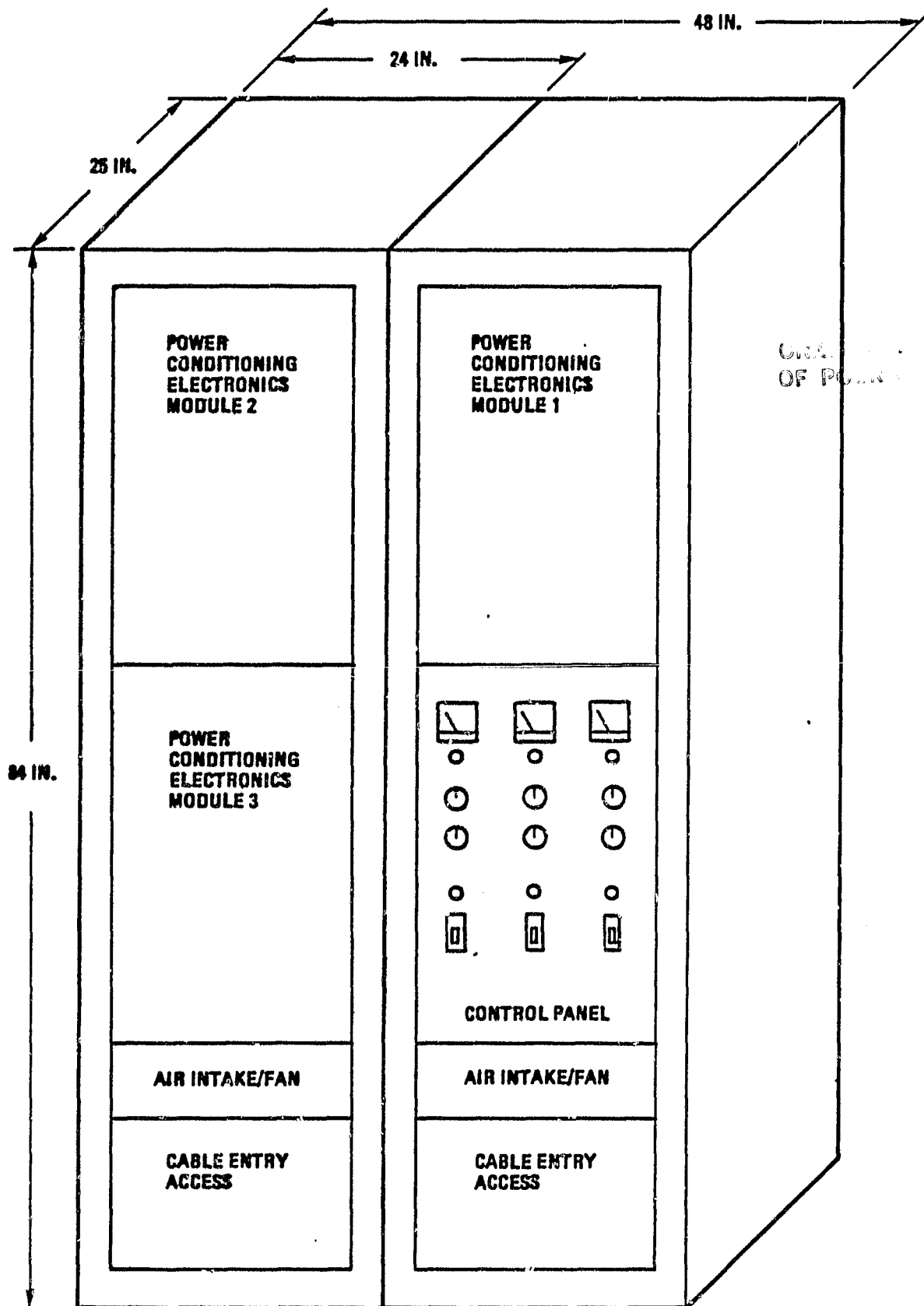


Figure 7-3. Solar Array Simulator Racks

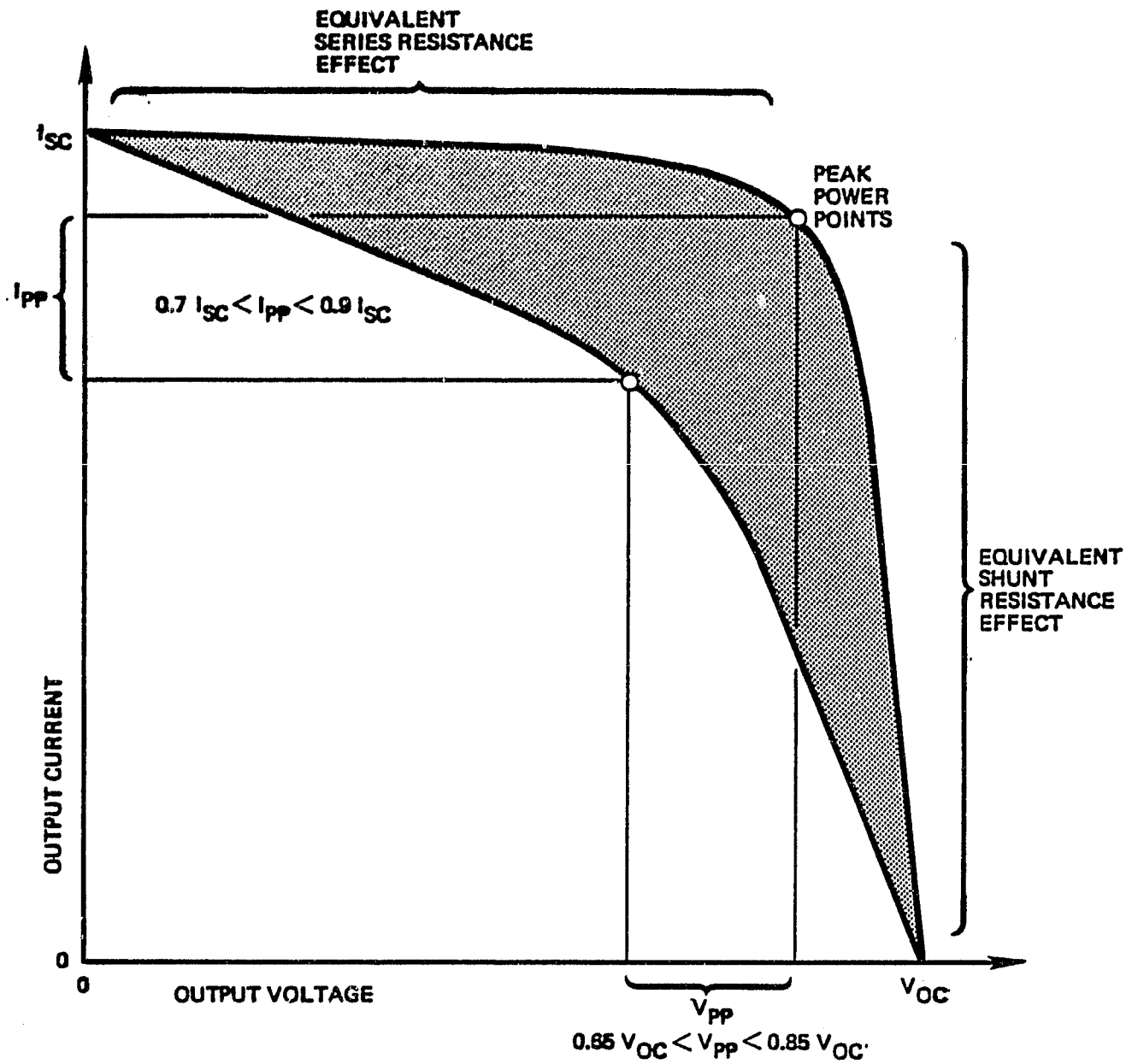


Figure 7-4. Shape of Output Characteristic is Adjustable

7.2 ENERGY STORAGE

Nickel-hydrogen cells of 150-ampere-hour capacity were selected as the energy storage devices of the reference electrical power system concept. These cells, however, are presently not available and would be relatively expensive items. Therefore, for the Test Facility, a commercial nickel-cadmium cell, incorporating a vented plastic container, pocket plate construction, and flooded electrolyte, is selected as a substitute cell (Section 6.1). These nickel-cadmium cells are readily available and relatively inexpensive, and may be appropriately oversized and selectively operated to be reasonably representative of nickel-hydrogen electrical performance.

The selected nickel-cadmium cell is a nominal 189-ampere-hour design manufactured by NIFE, Incorporated, as model H414 (Figure 7-5). This is a high discharge rate cell, and it has more plate surface area than corresponding low discharge rate cells. This larger plate surface area is selected to maximize the transient electrical response of the cell during discharge and thereby more closely represent nickel-hydrogen performance. The selected cell capacity of 189 ampere-hours is somewhat larger than the 150-ampere-hour nickel-hydrogen cell it is to simulate, but the polarization curves of this cell (Figure 7-6a) reasonably match the projected polarization curve for nickel-hydrogen performance (Figure 7-6b) at the full load operation of the power channel (16 kilowatts).

The NIFE H414 cells have plastic cases and are normally assembled in two- or three-cell blocks (Figure 7-7). Single cells are possible at extra cost. Each cell is heavy (32 pounds dry) and requires 4.65 quarts of electrolyte (potassium hydroxide, KOH). As vented cells, water must be added occasionally and the vent area wiped clean. The cells are typically mounted in an open stepped battery rack (Figure 7-8) for electrolyte servicing access. A four-step rack, approximately 15 feet long, will hold the 160 cells required for one battery.

Hydrogen gas is generated within these cells during overcharging and is vented to the local atmosphere. A mixture of 4 percent hydrogen and air is potentially explosive and should be avoided. The simplest safety precaution is adequate ventilation of the battery area to preclude hydrogen

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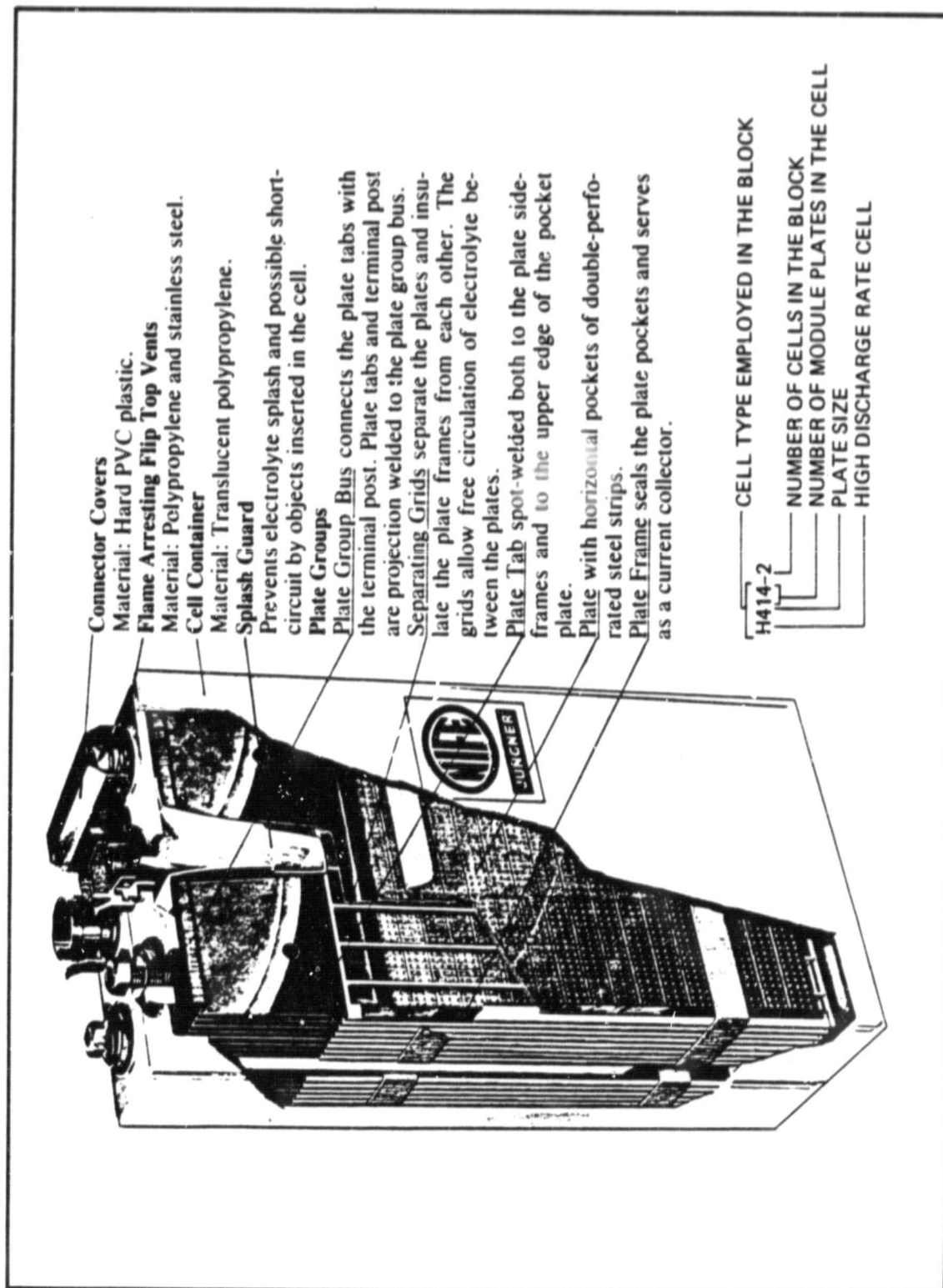


Figure 7-5. H414 Cell Construction

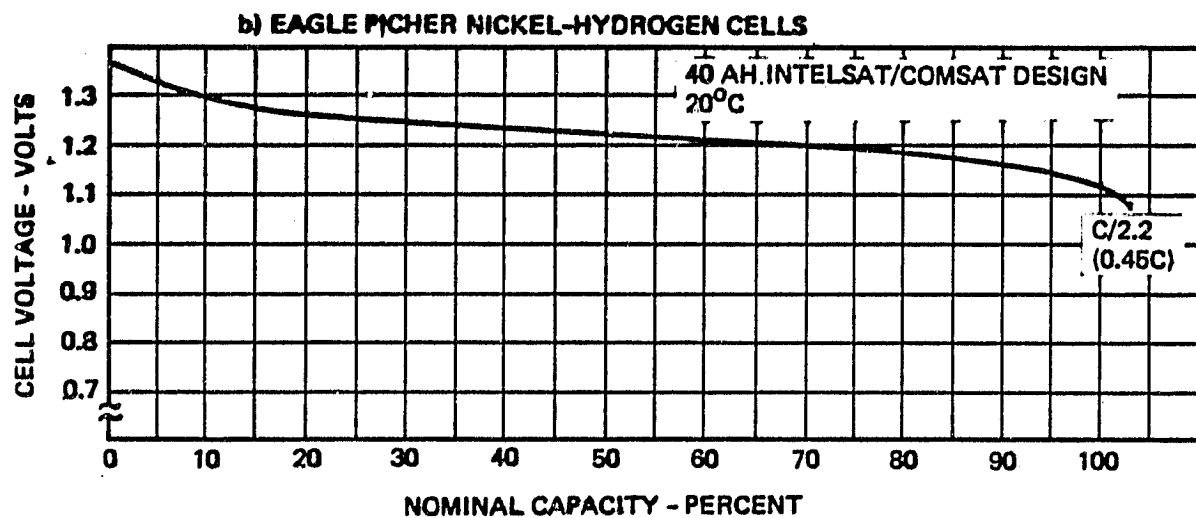
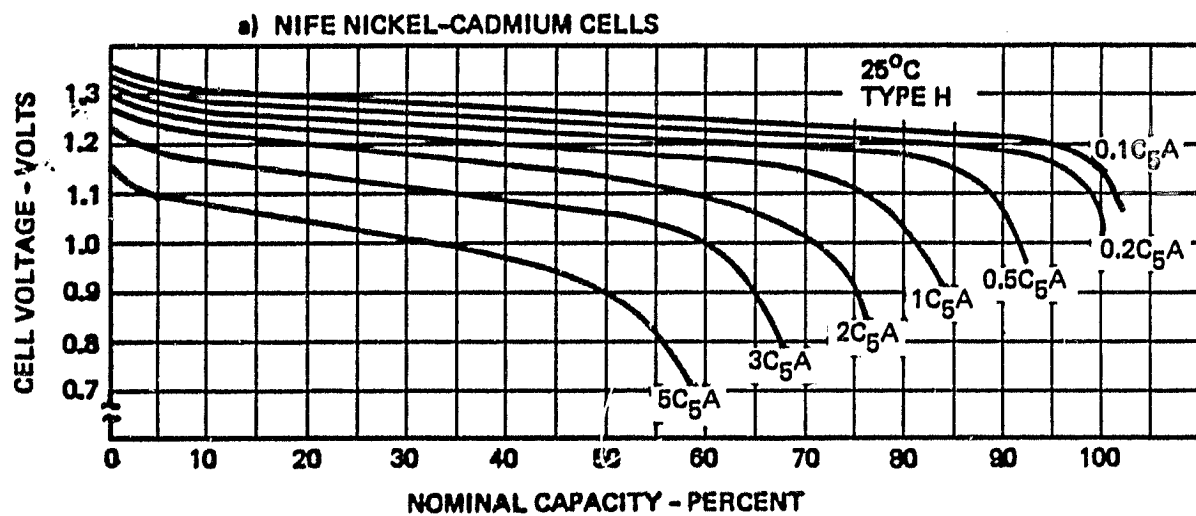
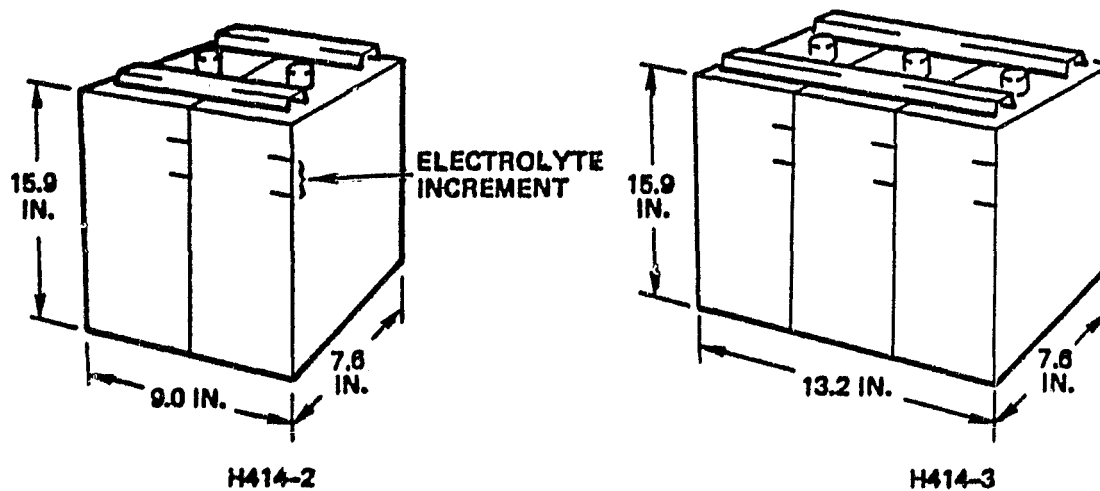


Figure 7-6. Polarization Curves Are Similar

CELL BLOCK PHYSICAL SIZE



CELL CAPACITY (5 HOUR RATE)

CELL WEIGHT (DRY)

CELL ELECTROLYTE (VOLUME)

ELECTROLYTE INCREMENT (VOLUME)

H414

189 AMPEREHOURS

32 POUNDS

4.65 QUARTS

0.90 QUARTS

Figure 7-7. NIFE H414 Battery Blocks

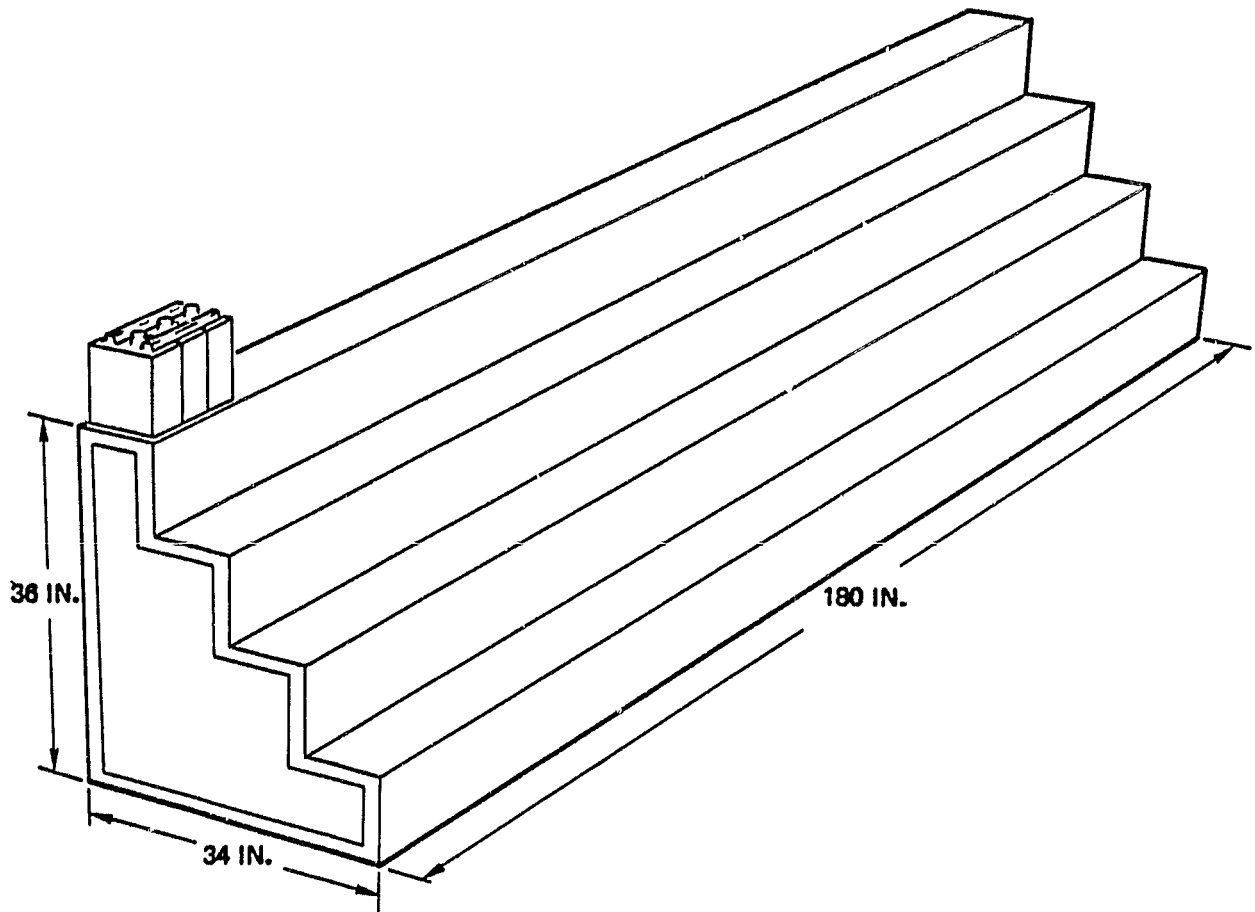


Figure 7-8. Battery Rack

accumulation to dangerous levels. Forced ventilation is typically used, with ventilation operated during the later portion of a charge cycle. Hydrogen detectors are recommended also for a redundant safety measure to initiate forced ventilation.

The cells are interconnected with cell-manufacturer supplied hardware (bus bars). In addition, connections at each cell are required for individual cell voltage monitoring. These wires should be as small as physically practical (26 or 28 gage) in order to fuse easily in the event of a fault. However, the insulation of these wires should be durable (glass fiber, not polyvinyl chloride) to prevent propagation of a fault to adjacent wiring in common cable harnesses.

Thermal sensors are required throughout each pack of battery cells. Twelve sensors are mounted on the battery, three per row of cells. Sensors are negative coefficient type thermistors with a nominal resistance of 4000 ohms at 25°C. Sensor power, and signal monitoring and conditioning, are provided by the temperature module cards for the Power Source Controller microprocessor.

Considerable caution must be exercised in the vicinity of these batteries. Any tool or personal metal (rings, jewelry, tie clips, watches, belt buckles, etc.) that shorts any battery or cell terminals will allow well over 1000 amperes of current to flow, lead to immediate welding of the metal in place, resistance heat the item red hot, and propagate these damaging temperatures to any adjacent materials (or people). Insulated covers are therefore provided for the cell terminals, and these must be installed and maintained.

7.3 BATTERY ANCILLARY PANEL

The Solar Array Simulator and the battery are connected together electrically to form the primary distribution bus of a power channel. This connection occurs at the Battery Ancillary Panel (Figure 7-9) and incorporates protection equipment (mechanical, high-voltage circuit breakers) for battery fault current rupture. In addition, support functions are included for current monitoring, for battery reconditioning discharge, and for direct trickle charge of the battery when the Test Facility is inoperative.

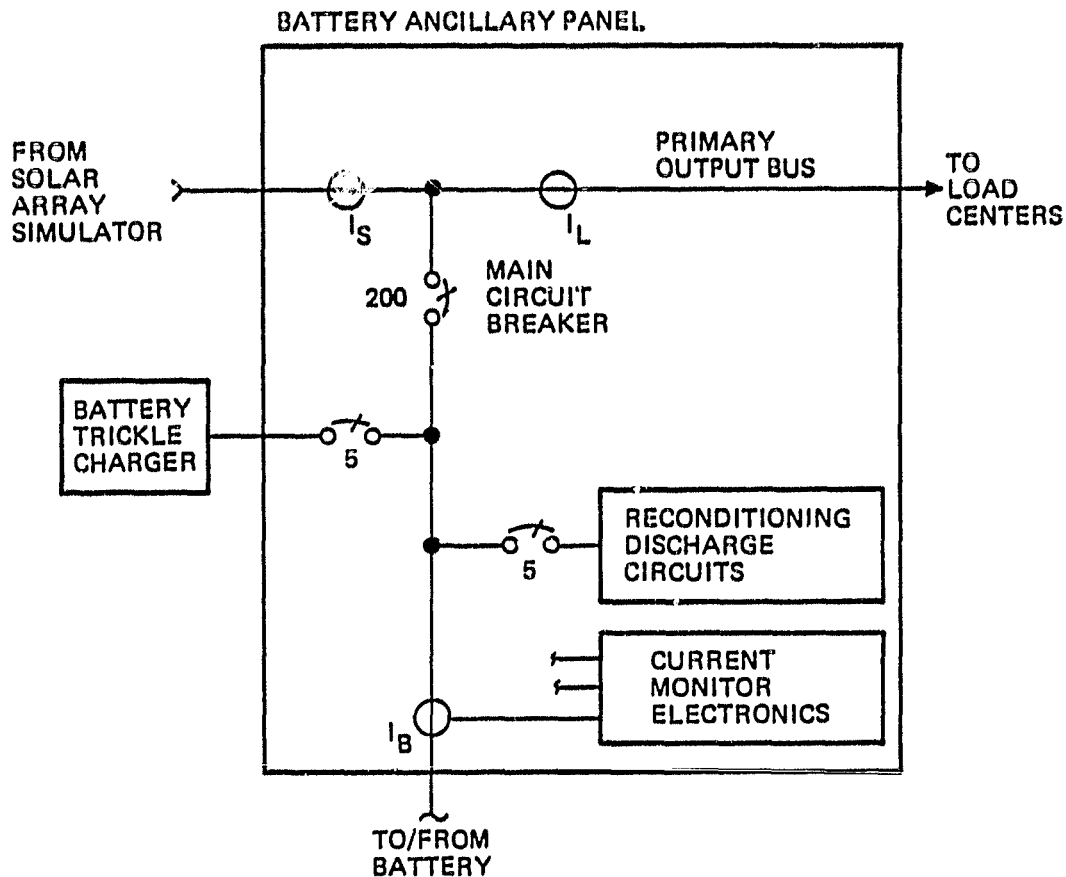


Figure 7-9. Battery Support Equipment

The Battery Ancillary Panel is located on the Power Source Controller rack for wiring convenience (Figure 7-10). This location minimizes unprotected power wiring as the Power Source Controller rack is adjacent to the battery cell rack (Figure 5-6).

3.1 Current Monitors

The battery current value is used for control of battery charging. It is utilized within the Power Source Controller in the control algorithm to regulate the solar array current output and to calculate the battery state of charge via ampere-hour integration. In addition, the Battery Ancillary Panel represents a convenient location to monitor solar array current and channel load current which also provide for a validation check of the battery current. Consequently, these current monitors are located on this

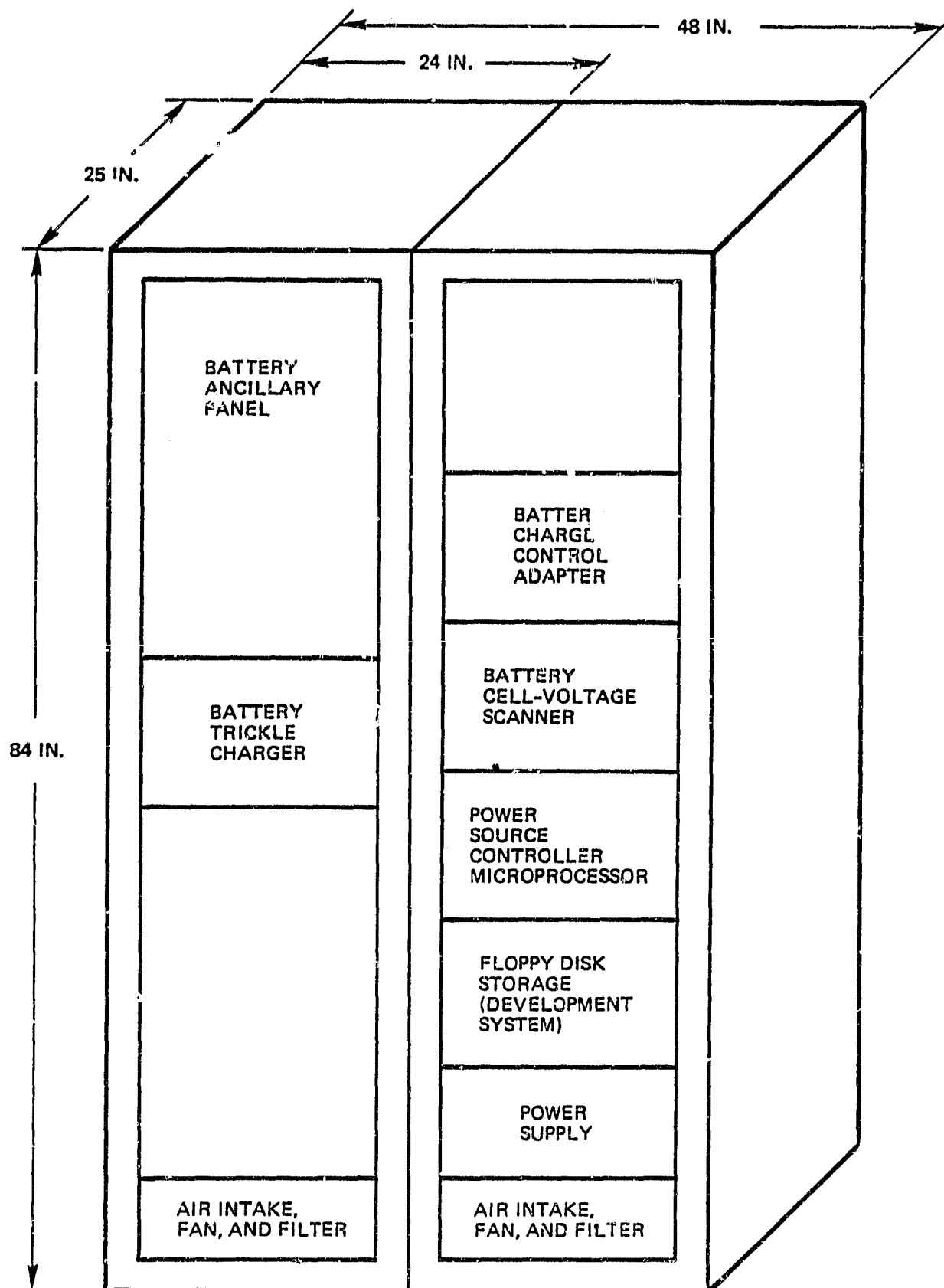


Figure 7-10. Power Source Controller and Ancillaries

panel, and the respective current values are thereby acquired via the Power Source Controller for subsequent application in the Power Management Subsystem.

7.3.2 Reconditioning Discharge

Reconditioning discharge is employed with nickel-cadmium cells on geosynchronous satellites to discharge essentially their full capacity. This deep discharge and the subsequent recharge reconditions the cells to more uniform performance. A sufficiently low discharge rate (C/100) is employed to assure that any cell reversal is relatively safe. Similar reconditioning may become appropriate for the nickel-hydrogen cells of the reference electrical power system operated in low earth orbit.

Little variation is expected in the performance of the selected commercial cells of the substitute nickel-cadmium battery for the Test Facility. However, performance variations will be deliberately introduced by shorting certain cells with low resistance during Test Facility operations to evaluate anomaly detection, evaluation, and accommodation features of the reference electrical power system concept. Subsequent removal of these shorts does not restore normal cell performance, and the entire battery must be essentially fully discharged and then recharged to restore performance (reconditioning). The reconditioning discharge circuit is therefore included to discharge the battery cells fully at an initial C/100 rate (2 amperes) with a 100-ohm, 400-watt, power resistor.

7.3.3 Trickle Charger

The commercial nickel-cadmium cells self discharge at a slow rate on open circuit stand. Consequently, the state of charge slowly reduces, but the cell capacity is unaffected. Recharging returns the battery to full charge. Alternatively, trickle charging can be used to maintain the battery at full charge.

During Test Facility operation, battery charging energy is provided by the Solar Array Simulator as controlled by the Power Source Controller. The amount of energy removed from the battery during eclipse (36 minutes in low earth orbit) is returned rapidly and fully during the subsequent 54 minutes of sunlight. Trickle charging of the battery from the Solar Array Simulator occurs during the latter portion of the 54-minute sunlight period

when maximum energy has not been removed from the battery during the prior eclipse. Hence, the Solar Array Simulator and Power Source Controller are the battery charger for "normal" system operation of the Test Facility.

During inoperative periods of the Test Facility (such as overnight, weekends, holidays, etc.), trickle charging of the batteries may be desirable to maintain the battery state of charge by minimizing self discharge depletion and thereby avoiding any need to recharge the batteries during reinitiation of the Test Facility operations. A manually initiated battery charger (power supply), operated from utility power (120-volt, 60-cycle) is included to maintain the battery state of charge during Test Facility inoperative periods. This battery charging compensates for the self discharge current (typically C/24,000 to C/2400) which would otherwise degrade the battery state of charge by 0.1 to 1.0 percent per day. A 250-volt, 150-milliamperere, direct-current power supply, operated from utility power (120-volt, 60-cycle), with an adjustable current control over the range 10 to 150 milliamperes, is required. The power supply is adjusted to essentially offset the self discharge effects of the battery.

7.4 POWER SOURCE CONTROLLER

The Power Source Controller provides the data processing and storage capability for the power source management functions of battery charging, battery state of health analysis, and battery degradation or anomaly accommodation. The major operational function is to control battery charging. In this mode, the Power Source Controller samples battery current, compares the battery current data to the desired charging current, and sends the appropriate error signal to the Solar Array Switching Unit (SASU) in the reference electrical power system concept to incrementally connect (or disconnect) solar array segments to the main bus of the respective power channel. This battery charging operation represents a closed loop control system with incrementally stepped responses of solar array current to battery current changes. In the Test Facility, the solar array and Solar Array Switching Unit are simulated by the Solar Array Simulator. Hence, the Power Source Controller interfaces with the Solar Array Simulator to control its output current.

The Power Source Controller consists of a microprocessor, memory, input/output (I/O) circuitry, and a data bus interface adapter (BIA). In addition, battery cell-voltage scanner electronics and appropriate power supplies are required. This controller is similar to the Load Center Controller (Volume 2). A Power Source Controller breadboard is being built* using commercially available Texas Instruments printed circuit cards, the TM 990/530 chassis, and a newly developed battery cell-voltage scanner. This breadboard hardware is mounted in a 19-inch cabinet (Figure 7-10) with suitable space for its supporting power supply and the Battery Ancillary Panel. This breadboard is appropriate for the Test Facility. Three controller breadboards are required, one for each power channel, and consequently two additional units must be constructed.

7.5 RESISTIVE LOADS

The proposed resistive loads aggregate 21 kilowatts per load center arranged as nine loads: three 4-kilowatt loads, three 2-kilowatt loads, and three 1-kilowatt loads. Each of these loads has three controllable power steps:

4 kW: 0, 2.5, 3.25, 4.0 kilowatts

2 kW: 0, 1.5, 1.75, 2.0 kilowatts

1 kW: 0, 0.5, 0.75, 1.0 kilowatt

This load step feature allows simulation of fluctuations within an individual load independent of the quantity of loads activated by the Load Center Controller. Such individual load fluctuations (individual load power profile) are hypothesized for actual payload packages connected to a common electrical load port of a load center. Remote control, utilizing the Simulation Profile Controller of the Test Facility Control Console, or local control of these steps, is provided. Pilot lamps and ammeters are included to enhance human visibility of the load operation. Fuses, air flow detectors, and cooling fan interlocks are required for load equipment protection. Similar resistive, incrementally stepped load banks have been built by Sotcher Measurement of Sunnyvale, California.

*NASA Contract NAS8-34539.

An initial packaging conceptual design (Figure 7-11) places a set of three loads in one standard electronic rack with its respective distribution switchgear. One electronic rack is utilized to house the Load Center Controller and supporting equipment. A preferred alternative is to mount the dissipative elements external to these cabinets and thereby minimize air cooling requirements. Remote resistive element location, external to the laboratory building and utilizing forced ambient air for cooling, is proposed to minimize the heat input to the laboratory air conditioning system.

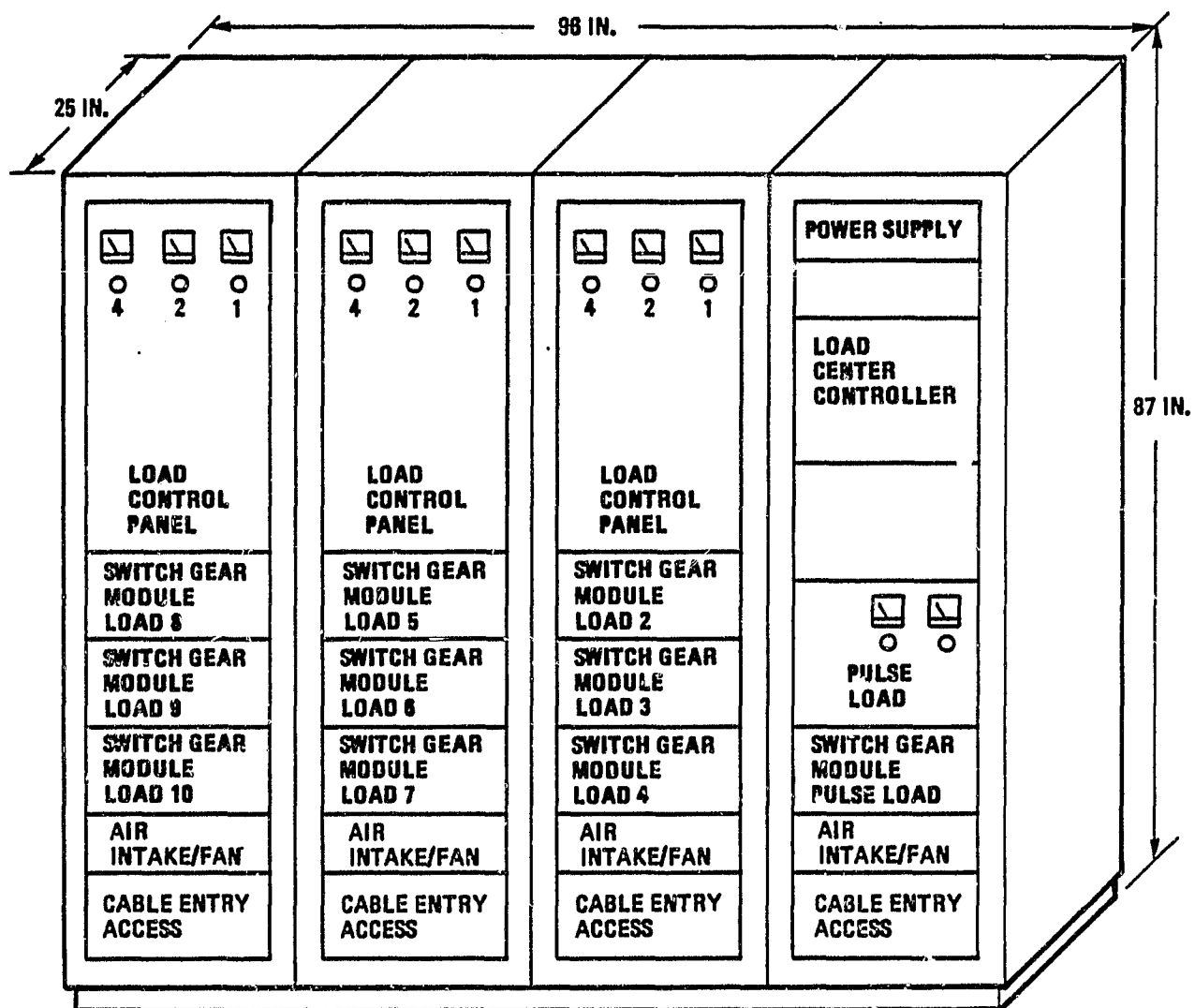


Figure 7-11. Load Center Packaging Concept

7.6 PULSE LOAD

Transistor Devices, Incorporated, of Cedar Knolls, New Jersey, produces a load simulator termed "Dyna-load". The Dyna-load simulates electrical loads to test power supplies, generators, servo systems, batteries, and similar electrical power sources. It simulates, at the option of the user, resistive loads, constant current loads, or constant voltage loads (similar to a battery or a zener diode). A provision is also included for external programming in automated test setups. The external programming voltage is from 0 to 6 volts with an input impedance of 5K minimum. Load current is directly proportional to programming voltage, and the sensitivity is adjustable with the front panel current adjustments. Pulsating loads, in the range of 0 to 5000 hertz, are thereby achievable.

Transistor Devices has designed and produced a Dyna-load (Model DPL 50-150-3000) rated at 0 to 50 volts, 0 to 150 amperes dc, and 0 to 3000 watts. Modest modification of this design is required to produce a 200 \pm 30 Vdc, 0- to 3000-watt unit. Such a unit is estimated to cost \$3500 by Transistor Devices, Inc., but this does not include any pulse programming function generation. An interface module is required in the Dyna-load modifications to allow the Simulation Profile Controller to provide the varying (analog) 0 to 6 volt command signal that defines the pulse load response. Two pulse load simulators are required, one for each load center.

7.7 SWITCHGEAR

The load center switchgear envisioned for the reference electrical power system concept performs the dual functions of switching to connect the load to a power channel main bus and protection (circuit breaker operation) in the event of excessive load bus current. Such devices for 250-volt operation with direct current are in the breadboard development stage at NASA/LeRC, but they are not available commercially, in quantity, nor at relatively low cost. Consequently, two large (bulky), 250-volt, direct-current, commercial devices - a manual circuit breaker and a relay - are connected in series to provide an electrically equivalent substitute (Figure 7-12).

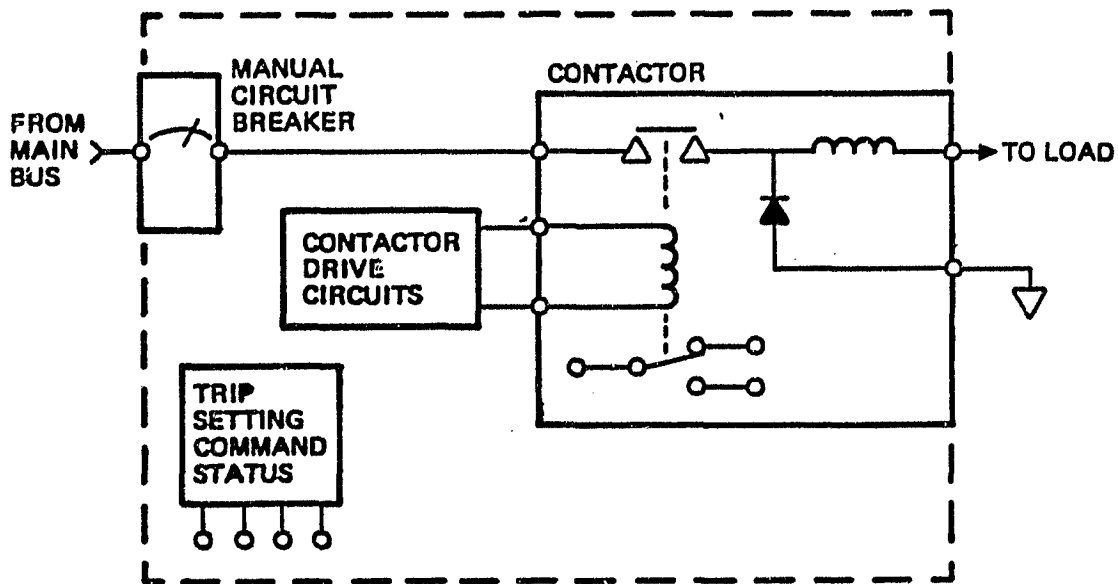


Figure 7-12. Load Center Switchgear Substitute

The circuit breaker (Figure 7-12) is a manual reset device, General Electric TED-series line breaker. These are available in 5-, 10-, 15-, and 20-ampere ratings which are suitable for the 1-, 2-, 3-, and 4-kilowatt loads, respectively. These circuit breakers are not programmable in their trip settings nor commandable electrically to reset. This is acceptable as the circuit breaker function is a protective feature and overloads are the exception. However, an indication circuit is added to the basic configuration to display the status of the commanded trip level from the Load Center Controller.

The contactor (Figure 7-12) is an electromagnetically operated, normally open, single-pole power relay, a Cutler-Hammer 6002 series D-C contactor. This contactor series is available with 25-ampere contacts and 5-, 10-, or 25-ampere blowout coils and is compatible with the currents of the 1-, 2-, 3-, and 4-kilowatt loads. An auxiliary contact is available with the basic contactor and selected to provide an independent circuit for status monitoring of the contactor. In addition, a drive circuit is required to provide latching operation from the momentary Load Center Controller commands and to amplify the low level signals from the Load Center Controller into the required coil power of the contactor.

Two (or three) such switchgear substitutes (Figure 7-12) are required for each load bus (Figure 5-8). In addition, load current and voltage monitors are required to supply this data input to the Load Center Controller. Hence, the two (or three) switches and the current and voltage monitors for one load bus are packaged on a single panel chassis (Figure 5-9). This packaging concept allows simplified replacement of each switchgear module with advanced technology switchgear development breadboards for subsequent operation and testing.

7.8 LOAD CENTER CONTROLLER

The Load Center Controller commands the load bus switchgear in response to directions from the Electrical Power System Controller via the data bus and subsequently monitors the results (both switchgear response and load-bus parameters). Discrete commands control switchgear on/off operation, and parallel digital commands set the overload shutdown parameters of spacecraft switchgear envisioned for the reference electrical power system concept. The switchgear status (on, off, tripped) and the load-bus current and voltage (analog) are monitored (inputs). Data is thereby available in the controller for determination of switchgear operation and, if required, definition of any corrective action required (new commands).

The Load Center Controller hardware consists of a microprocessor, memory, digital output and analog input circuitry, and a data bus interface adapter. In addition, high level buffers are associated with the output switchgear commands, and a power supply (+12, +5, +24 volts) is required. A breadboard of the Load Center Controller (Figure 7-13) was built (Volume 2) using commercially available printed circuit cards, chassis, and adapter modules from Texas Instruments; a commercial power supply of modular construction from AC/DC Electronics; and a 19-inch cabinet rack. This breadboard is appropriate for the Test Facility. Two controller breadboards are required, one for each of the two load centers, and consequently a second breadboard Load Center Controller must be constructed.

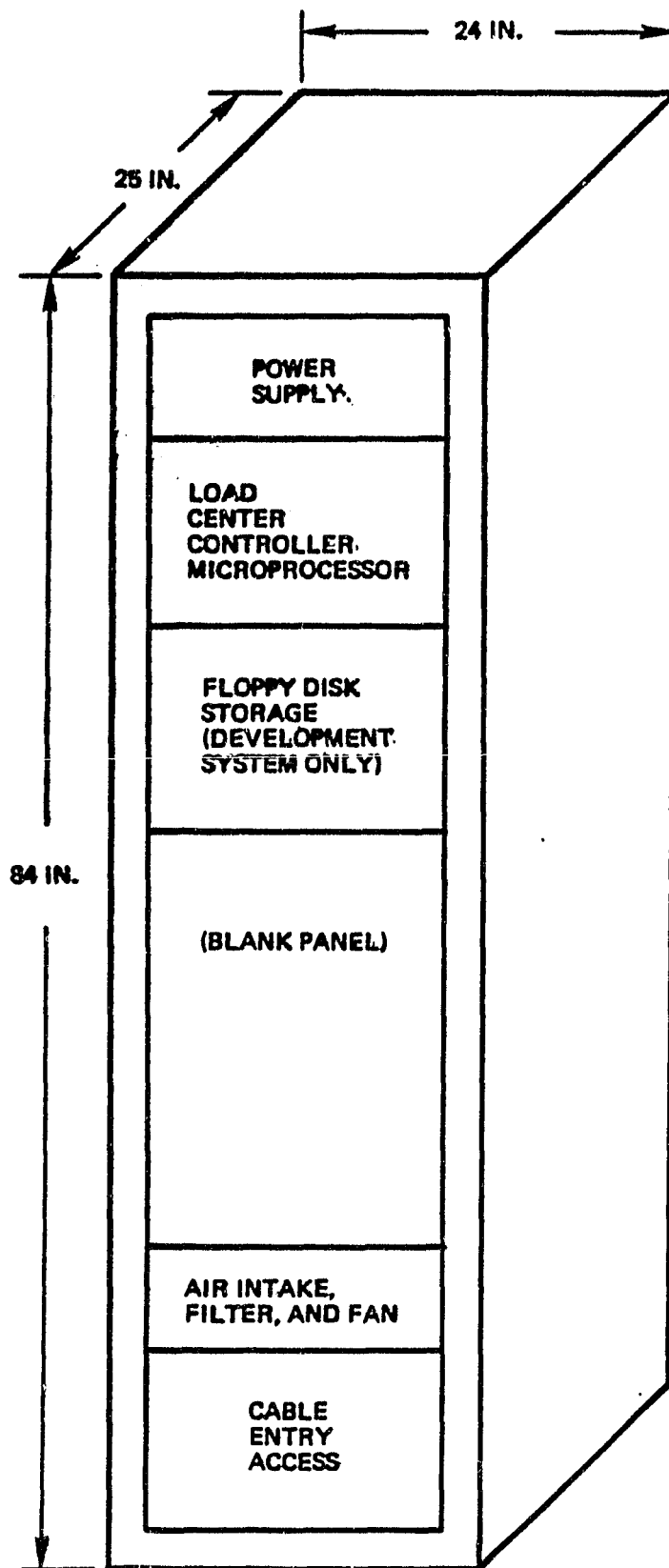


Figure 7-13. Load Center Controller

8. CONCLUSIONS AND RECOMMENDATIONS

The conceptual design for the AMPS Test Facility comprises three power source channels, each representative of one of the multiple channels of the reference electrical power system of Volume 1. Each power generation/energy storage channel of the Test Facility is rated at 16 kilowatts, for a total Test Facility capacity of 48 kilowatts. The Test Facility includes two identical power distribution load centers of 24 kilowatts each and incorporates various hardware simulations or substitutions when spacecraft equipment or prototypes are not available or appropriate.

The Test Facility concept also includes a Control Center to provide the interface simulation between the electrical power system and the other spacecraft and ground systems, e.g., the spacecraft computer, ground controller, and test center personnel (or equivalent onboard spacecraft personnel). Video displays and computer keyboards (terminals) are provided to enable personnel to communicate with the power management subsystem of the electrical power system and with the simulation profile controller of the Control Center. In addition, display panels, similar to utility generation station status panels, are included to depict the continuing status of the electrical power system.

The goals and requirements for the Test Facility are effectively met with this design. Three high-voltage, power source channels of the multichannel electrical power system are faithfully represented including power generation, energy storage, and fault protection equipment, and power management subsystem hardware. Similarly, the two power distribution load centers simulate the power switching, protection, and power distribution management equipment of a high-power spacecraft. Power system loading is accomplished by the resistive and dynamic load banks associated with these load centers. In addition, various degradation and failure modes may also be simulated, the response of the electrical power system, its management features, and the characteristics of individual components may be observed and recorded, and their performance demonstrated and tested.

The Test Facility equipment is modularized, and any component may be replaced by hardware samples (breadboards or prototypes) of advanced technology for system testing. Also, the power capability of the Test

Facility may be enlarged, either in the power capacity of a single channel, or by adding power source channels, and with additional loads and/or load centers.

The AMPS Test Facility requires a three-part program to bring this Test Facility to fruition. Power hardware must be designed and specified, fabricated (or procured), and assembled and integrated into the power channels and load centers. Additional power management subsystem controllers must be assembled and integrated with their respective power equipment. Specialized Control Center equipment must be designed and fabricated. Finally, the control algorithms and their associated software coding must be developed and implemented to operate the electrical power system and the interfacing Control Center. Cost estimates, in 1981 dollars, aggregate \$1,780,000 (Table 8-1) for an operational AMPS Test Facility at NASA/MSFC, exclusive of NASA building modifications.

Table 8-1. Test Facility Cost Estimate

Equipment and Tasks	Cost (1981 K\$)
Power Hardware	456
PMS Hardware	513
Algorithm Development	456
Integration and Demonstration	154
MSFC Installation	201
Test Facility Cost	1,780

The goal of the AMPS Test Facility is to support the design and interactive development of a generic power management subsystem and to facilitate the integrated test evaluation of subsystem components for complex high-power spacecraft such as the Space Station and space platforms. Present prognosis infers a 1987 operational need date for the Test Facility. A funding schedule (Table 8-2) is therefore provided which would lead to operational readiness at the end of 1987. Initial funding is low, consistent with the usual start-up budget constraints. However, as tasks

Table 8-2. Inflation and Task Deferral Increases Costs

Fiscal year, AD	1982	1983	1984	1985	1986	1987
Assumed inflation rate, percent	15%	10%	10%	10%	10%	10%
Cumulative inflation multiplier	1.15	1.25	1.39	1.53	1.68	1.85
Program annual expenditure, K\$	272*	206	588	686	702	512
Cumulative program expenditures, K\$	272	478	1066	1752	2454	2966

*Contract NAS8-34539 in progress.

are deferred, they become concentrated into a few years to meet the 1987 operational goal, and the required annual funding rates become relatively large. In addition, the deferral of more tasks to later years increases costs, when stated in current dollars, due to inflation/cost-of-living escalation of the costs associated with these deferred tasks. This further increases the funding rates required in later years to meet the 1987 operational goal.